UNSTEADY SWIRLING FLOWS IN GAS TURBINES

Annual Technical Report

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1. *Program Objectives and Overall Plan*

Overall objective is to acquire fundamental understanding of a phenomena characterized by violent fluctuation induced by swirling flow -- 'vortex whistle', often found to occur in various aircraft engine components. By conducting a comprehensive and systematic investigation into the 'vortex whistle', we intend to achieve the following specific goals:

(1) by performing analysis to predict the frequency of vortex whistle and verifying it against the experimental results, one can detune the natural frequencies of engine components away from them in order to ensure their structural integrity,

(2) by appealing to the mechanism of acoustic streaming induced by vortex whistle, we will attempt to explain, through both analysis and experiment, the transformation of steady radial profile, in particular the total temperature separation or the Ranque-Hilsch tube effect, and

(3) based on the knowledge thus accrued and by exploring means to enhance the Ranque-Hilsch tube effect while avoiding the flow-induced vibration problem, we will conduct a feasibility study to exploit the temperature separation in aircraft engine components -- for example, its potential use for turbine cooling.

The entire program, comprised of both theoretical and experimental investigations, are divided into three phases:

Phase I . . . . . Preliminary analysis and construction of a test rig to investigate vortex whistle (April 1, 1978 to March 31, 1980)

Phase II . . . . data acquisition for a vortex whistle in a single cylinder and refinement of analysis (April 1, 1980 to Sept 30, 1981)

Phase III . . . experiment of vortex whistle within a co-annular duct and feasibility study to exploit the Ranque-Hilsch tube effect for turbine cooling. (October 1, 1981 to Sept. 30, 1982)

The objectives of Phase I were twofold: one was to lay out the basic analytical formulation, and from it, to obtain the preliminary theoretical explanation of the problem. Specifically, the effort was focused on devising a flow model which is simple enough to be amenable to analysis, but still captures the essential physics and exhibits the key feature of the 'vortex whistle' phenomenon. The second objective was, based upon the insight gained from the analysis, to design and construct an experimental test rig; it is basically, a single pipe within which air, injected tangentially, flows in a swirling motion.

The objectives of Phase II activities were (a), using the rig built in Phase 1, to acquire experimental data to make comparisons with the preliminary theoretical prediction and (b), to continue and refine the analysis. For a single pipe with tangential inlet of air, the unsteady characteristics as well as the amount of the temperature separation were measured; then by designing and installing acoustic suppressors, the effect of reducing the intensity of vortex whistle upon the temperature separation were to be observed. The analytical effort was aimed at adding necessary refinement to the preliminary results of Phase 1.

In Phase III, the effect of inner cylinders upon the unsteady flow field and temperature separation are to be investigated in a co-annular test rig provided with variable inlet vanes. Then, efforts will be expended to increase

the temperature separation by increasing the peak-to-peak amplitude of vortex whistle through external reinforcement of spinning waves. Synthesizing all these results, a feasibility study to explore the potential of temperature separation induced by vortex whistle for turbine cooling will be carried out.

2. *Features of 'vortex whistle' Phenomenon*

"Vortex whistle" --- this is the sobriquet we use in this report to describe one of the treacherous flow-induced vibration phenomena encountered in gas turbines. It is a spontaneous violent fluctuation that occurs in any swirling flow--including, but not necessarily restricted to, gas turbines. When the vortex whistle does occur in gas turbines, the induced vibration can sometimes become so severe that the blades and other structural members suffer serious damage. In addition to its obvious implications related to aeroelastic problems, its significance as a potential source of engine noise appears to have received scant, if any, attention and merits serious consideration. More important, experimental evidences to be recounted shortly disclose the unsuspected fact that the vortex whistle can metamorphose the very steady flow field, both in velocity and temperature distribution; that is, fluctuating, unsteady (a.c.) components of flow somehow interact with the time-averaged, mean (d.c.) components and alter them. The implications of this are obvious in raising serious questions about interpreting what has presumed to be steady data in compressors and turbines; in addition, beyond the confines of turbomechinery technology, they yield a clue to explain the dimly foreseen mechanism of energy separation in swirling flow, the so-called Ranque-Hilsch tube effects.[1,2]

Vortex whistle can be characterized by the following key features. First, it is induced by the presence of strong swirl. Second, it is a pure tone noise and its frequency increases proportionately to the flow-rate or swirl. It turns out that the presence of such rotating surfaces as rotor blades is not really necessary to produce the vortex whistle. The whistle can be found

even in swirl created by the tangential injection to a stationary cylinder. Historically it was, in fact, in this arrangement where Vonnegut[3] first discovered, in the swirling flow, the presence of a pure tone noise whose frequency increases proportionately to the flow rate. Because of the continuous change in frequency, he found that one can play musical tunes by varying the blowing pressure by mouth. It was Vonnegut who coined the name vortex whistle for this musical instrument and it is due to this reason that we call the similar descrete tone in swirling flow by this term. (For other earlier investigations, see Michelson[4], Suzuki[5] and Chanaud[6,7].) What elicits our extreme interest in the present context is the highly suggestive circumstances where Vonnegut was led to his finding of vortex whistle--he discovered it while working on the application of the Ranque-Hilsch tube effect(8).

In gas turbines, vortex whistle is known to occur in various components such as downstream of inlet guide vanes of radial flow duct[9,10], a ring chamber[11], and turbine cooling air cavity. Instances are known where vortex whistle in the swirling flow of cooling air cavity seriously jeopardized the structural integrity of turbines.

Recently, the problem of vortex whistle has unexpectedly presented itself in the test rig called an annular cascade built by General Electric Company, Evendale, Ohio under the USAF sponsorship to investigate some flutter characteristics of compressor blades in the non-rotating environment[12,13,14]. As a whole, the annular cascade is in the shape of a stationary duct formed between inner and outer casings; swirling air created by the variable vanes enter the test section, where the test cascade airfoils are nominally mounted on the outer casings. The whistle revealed itself in the check-out phase of the annular cas-

cade and its presence was detected even after the removal of the test airfoils; the frequency of the whistle was found to increase almost proportionately to the flow rate. The dynamic fluctuation was so intense as to endanger the subsequent test of bladings. Hence, dynamic measurement of the whistle has been carried out to seek means to suppress the whistle. Based upon this, the cascade was installed with acoustic suppressors and the unacceptable dynamic flow disturbance was finally removed. Since then, the vehicle has successfully been in use for aeroelastic purposes and served to identify some important aspects of flutter.[13].

Although the problematical vortex whistle has been eliminated from the annular cascade, the measurements made at a time when the whistle was still present offers us an opportunity to examine this unsteady phenomena in some detail. In addition to the observed increase of frequency proportional to the flow rate, the data, taken when the test airfoils are removed, reveals the following unexpected change in the steady or time-averaged flow field. When the whistle was inaudible, the steady-state tangential velocity distribution in the radial direction was in the form of a free vortex; the steady-state temperature was uniform. However, when the whistle became intense, then above a certain swirl, the tangential velocity near the inner wall became, abruptly and considerably, reduced, the radial profile transformed from a free vortex into one somewhat similar to a forced vortex; furthermore, what is utterly surprising is that the total temperature, initially uniform at the inlet, spontaneously separated into a hotter stream near the outer wall and a colder one near the inner wall, with the difference as large as 35°F. This latter vividly reminds us of the Ranque-Hilsch effect[1,2]. Take note of the fact that, upon the installation of the acoustic suppressors, which had succeeded in eliminating the vortex whistle,

the deformation in the radial profiles of velocity and temperature vanished.

Besides these observations recorded in the annular cascade, additional incidents observed in the other test rig disclose much the same phenomenon. In a radial in-flow test rig of Detroit Diesel Allison, Indianapolis, Indiana[9], the vortex whistle, apparently induced by swirl created downstream of inlet guide vanes, was detected beyond a certain flow rate; corresponding to the initiation of the sound, the total pressure, measured at a certain traverse point downstream of the inlet guide vanes, exceeded its upstream incoming value and at the same time, the exhaust pipe became noticeably warm when touched by hand, while the formation of ice was detected on the surface of the back plate at a location corresponding to the centerline of the pipe; furthermore, the maximum Mach number and mass flow was considerably lower than expected. The installation of the acoustic suppressor eliminated, as before, these anomalous effects and resulted in increasing the maximum Mach number and flow by 30%.

Similarly, in a radial compressor[10] of AiResearch Manufacturing Company, Phoenix, Arizona, a loud whistle in the downstream section of the inlet guide vanes posed a serious aeroacoustic problem, in addition to the deterioration of performance caused by the deformation of radial profile of the temperature.

In these, the acoustic streaming[15], or the d.c. components induced by the periodic disturbances, did somehow distort the steady flow field.

3 *Significant Achievements to Date*

The following is a summary of significant results accrued in the course of Phase I and Phase II; the latter being still in progress, the status report presented herein is as of June, 1981.

(A) Analysis

By posing model problems, the effect of periodic disturbances in a swirling flow was studied. The results, the details of which are available, the previous annual report, as Ref. 16, are presented as an AIAA paper, Ref. 17; therefore, only a brief synopsis is given below.

The linearized form of the periodic disturbances, are assumed to be a helically advancing wave with wave numbers specified in both axial and tangential direction; these constitute the leading terms of unsteady flow field. The fundamental frequency of periodic disturbances are determined by solving the linearized governing equation. In addition, the second order terms, whose time-averaged components generate acoustic streaming and other higher order terms are studied systematically by applying the method of the matched asymptotic expansion to the full compressible and unsteady Navier-Stokes equations.

The results of the linearized analysis shows that the frequency increases nearly proportionately to swirl, both for a swirling flow within a co-annular duct and a single pipe; this linearity is one of the key features of vortex whistle, as already pointed out.

As for the acoustic streaming for a co-annular duct where the base steady flow is taken to be of free vortex type, the tangential streaming near the inner cylinder displays the reversal of streaming direction at certain threshold swirl; in the neighborhood of threshold, the magnitude of streaming becomes sizeable. This implies that, beyond the threshold swirl, the magnitude of

entire swirls - - a sum of base steady swirl and acoustic streaming - - becomes reduced near the inner cylinder. Thus the initially imposed base flow of free vortex distribution becomes deformed to one not unlike a forced vortex.

With regard to the acoustic streaming in a single pipe where the base flow is assumed to be of Rankine vortex, the tangential streaming near the tube periphery is found to become infinitely large for the first tangential mode ($m = 1$ mode) and this remains so regardless of the magnitude of the base swirl. If and when such a disturbance is excited, this tends to deform the base Rankine vortex into a forced vortex.

Therefore, both for a co-annular duct and a single pipe, the transformation of the swirl into a forced vortex type results in the radial separation of the total temperature or the aforementioned Ranque-Hilsch tube effect.

(B) EXPERIMENTS

The experiments, to be detailed below, have been conducted for swirling flow in a single pipe and indeed verified the key features of the analysis -- (a) the presence of the vortex whistle whose frequency changes proportionately to the flow and (b) the temperature separation in the radial direction or the Ranque-Hilsch effect is directly linked to the acoustic streaming induced by the vortex whistle.

(B-1) ORIGINAL TEST RIG, INSTRUMENTATION AND RESULTS

As an initial test rig, a simple geometry of a single pipe with fixed tangential injection was selected. The main dimension was chosen in such a way to simulate the configuration of a commercially available Ranque-Hilsch tube (Vortec Corporation, Model No. 328-100). The main pipe of 9" nominal length and $\frac{11}{16}$" diameter was connected to a manifold section where a swirl generator, with tangentially drilled slots inclined 72^{o} from the radial direction, was installed (see Figure 1). An opening provided at the other end of the manifold discharges the colder air, while the open end of the main pipe, where a flow controlling valve is placed, serves as the exhaust for the hotter air. The main pipe, initially 9" long, is made of 4 detachable segments, the ends of which are all threaded, so that the length can be adjusted; the length of the pipe being reduced to the minimum of 2 $\frac{1}{4}$".

The pressurized air supplied from a high pressure air tank, after passing through a flow-metering orifice and a sound muffler, is fed to the manifold. The entire test assembly is placed within a reverberation chamber.

With respect to the instrumentation, a $\frac{1}{8}$" diameter Alumel-Chromel thermocouple immersed in the muffler measures inlet temperature, while two thermocouples, one placed at the hot air exhaust and the other at the cold air discharge, serve to indicate the hot and cold air temperature, respectively. The sound

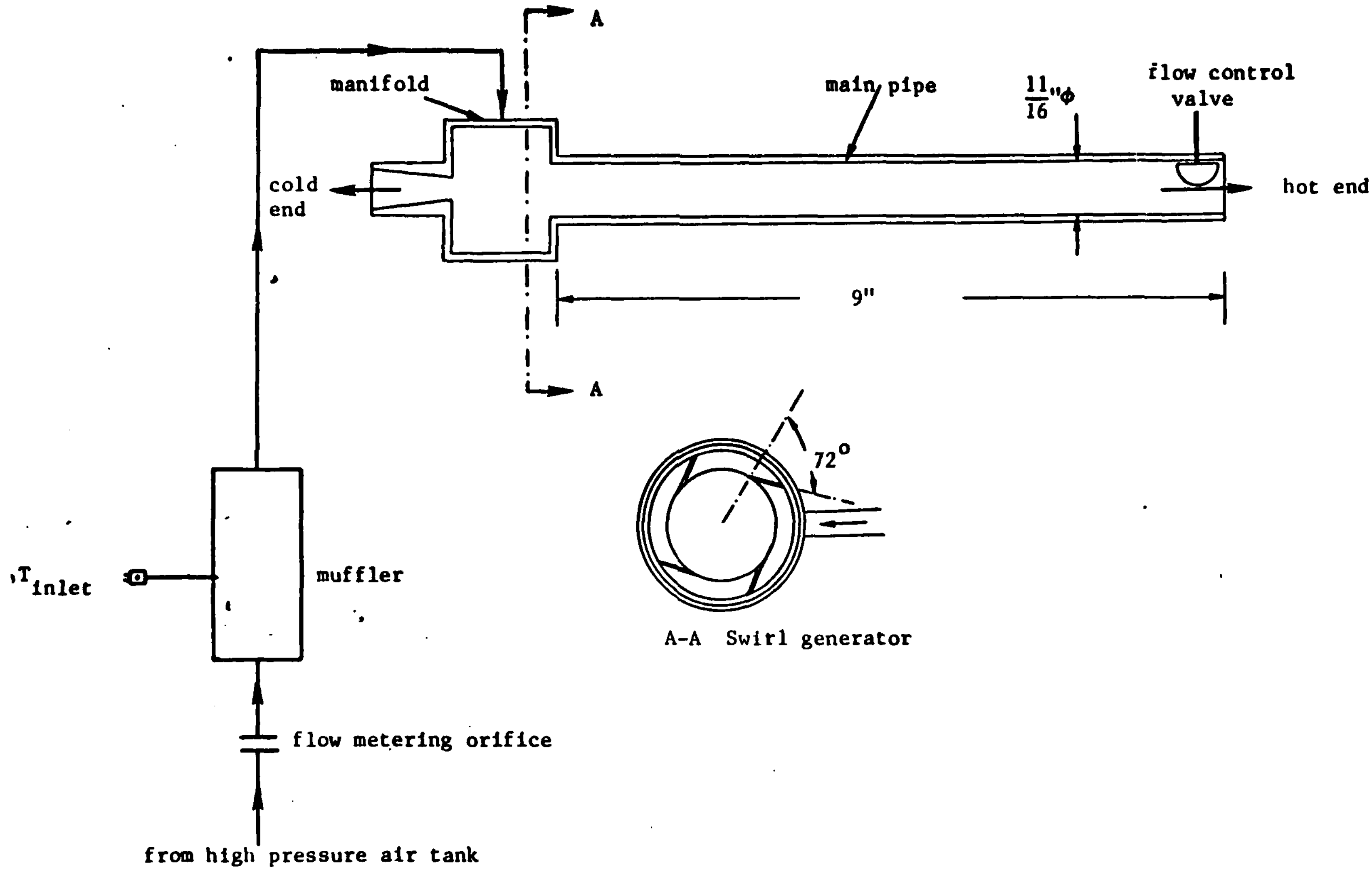

A
A
manifold
main pipe
11/16"ϕ
flow control
valve
cold
end
hot end
9"
72°
T inlet
muffler
A-A Swirl generator
flow metering orifice
from high pressure air tank

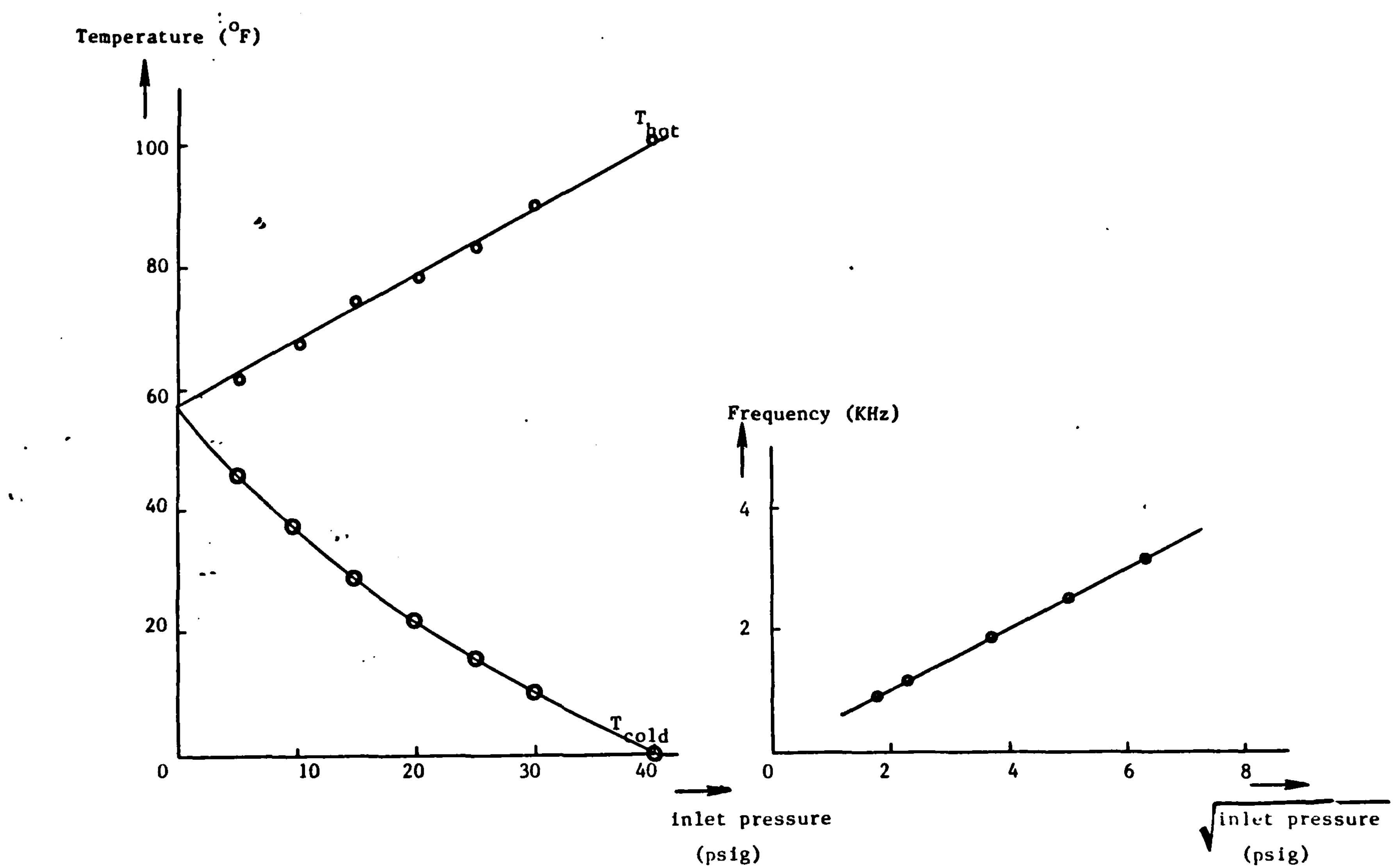
FIGURE 1

signal, received by a $\frac{1}{4}$" condenser-microphone (Bruel and Kjaer, Type 4135) mounted 3' away from the test section, is fed into either a $\frac{1}{3}$ octave frequency analyzer (Bruel and Kjaer, Type 2112) or a mannually scanned narrow band frequency analyzer (Singer Universal Spectrum Analyzer, MF-5)

Initial check-out test of the rig immediately revealed the following: (1) the air separates into hot and cold streams, each discharging out of its corresponding openings and (b) also a vortex whistle or pure tone, whose frequency increases as the flow increases, is dominant over the entire frequency spectra. Figure 2 displays such a temperature separation and the fundamental frequency of the vortex whistle, where in the latter its almost linear dependence upon the square root of its inlet pressure, measured in gauges, indicates that the frequency is proportional to the flow rate or swirl. Figure 3 typifies the data of $\frac{1}{3}$ octave frequency spectra, where, besides the dominant fundamental frequency around 2KHz, the presence of its second harmonic around 4KHz is observed. All data corresponds to such position of hot end valve as adjusted to yield the maximum temperature separation between the two air streams exhausting from hot and cold ends.

(B-2) MODIFIED TEST RIG AND SOME COMPARISON WITH ANALYSIS

According to the analysis, such a temperature separation, which takes place in the radial direction, should occur right near the junction of the main pipe with the manifold so long as the vortex whistle which induces such a separtion exists. Therefore, the initial length of the main pipe was reduced from 9" to 2 $\frac{1}{4}$" and even in this short section, the presence of temperature separation and the vortex whistle was confirmed. Subsequently, the initial counter-flow type, where the hot air escapes from one end while the cold air exhausts from the other was modified to a uni-flow type, Figure 4; by



Temperature (°F)
100
80
60
40
20
0
10
20
30
40
T_{hot}
T_{cold}
inlet pressure
(psig)
Frequency (KHz)
4
2
0
2
4
6
8
$\sqrt{\text{inlet pressure}}$
(psig)

FIGURE 2

Test #53

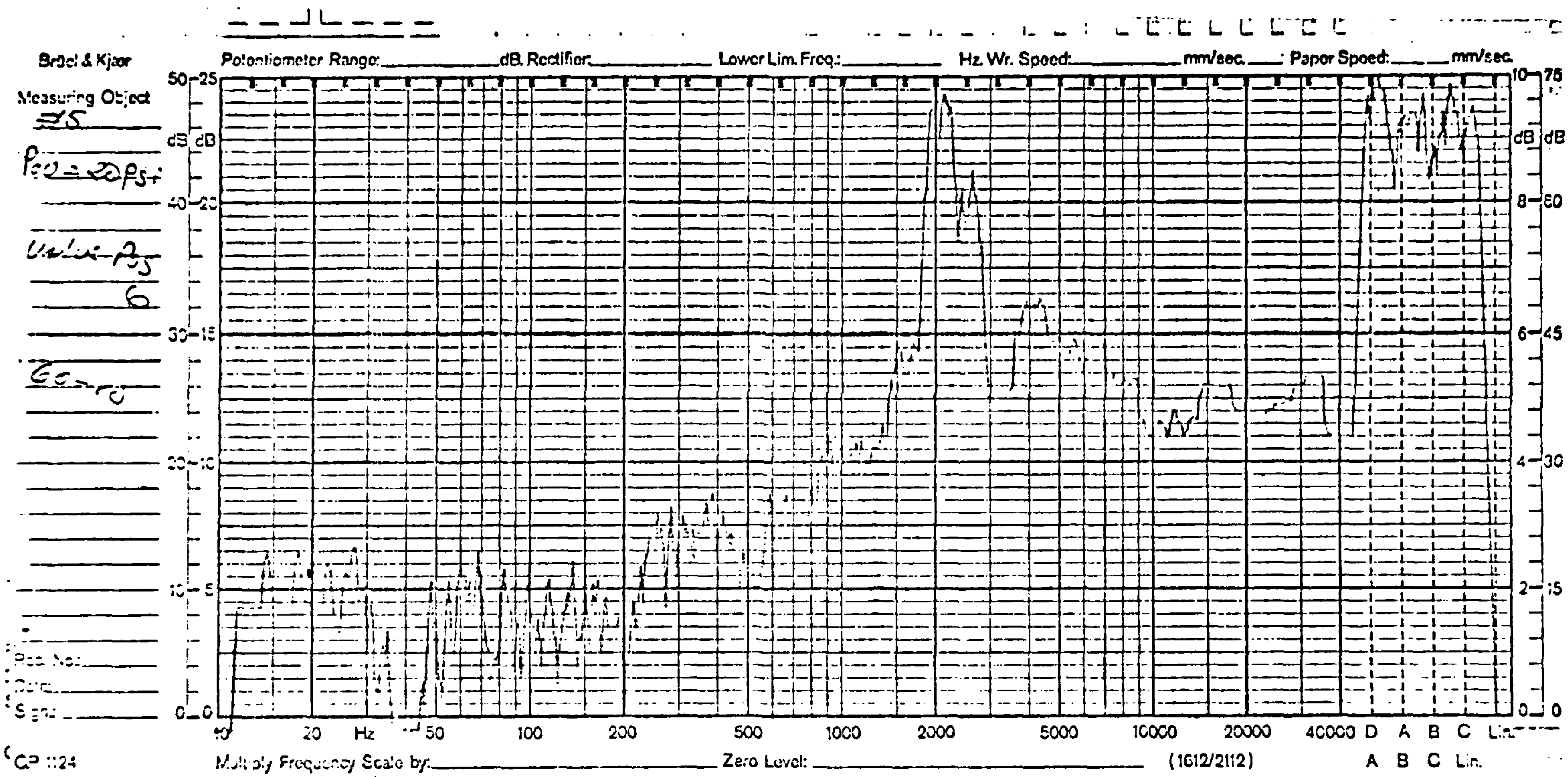


FIGURE 3

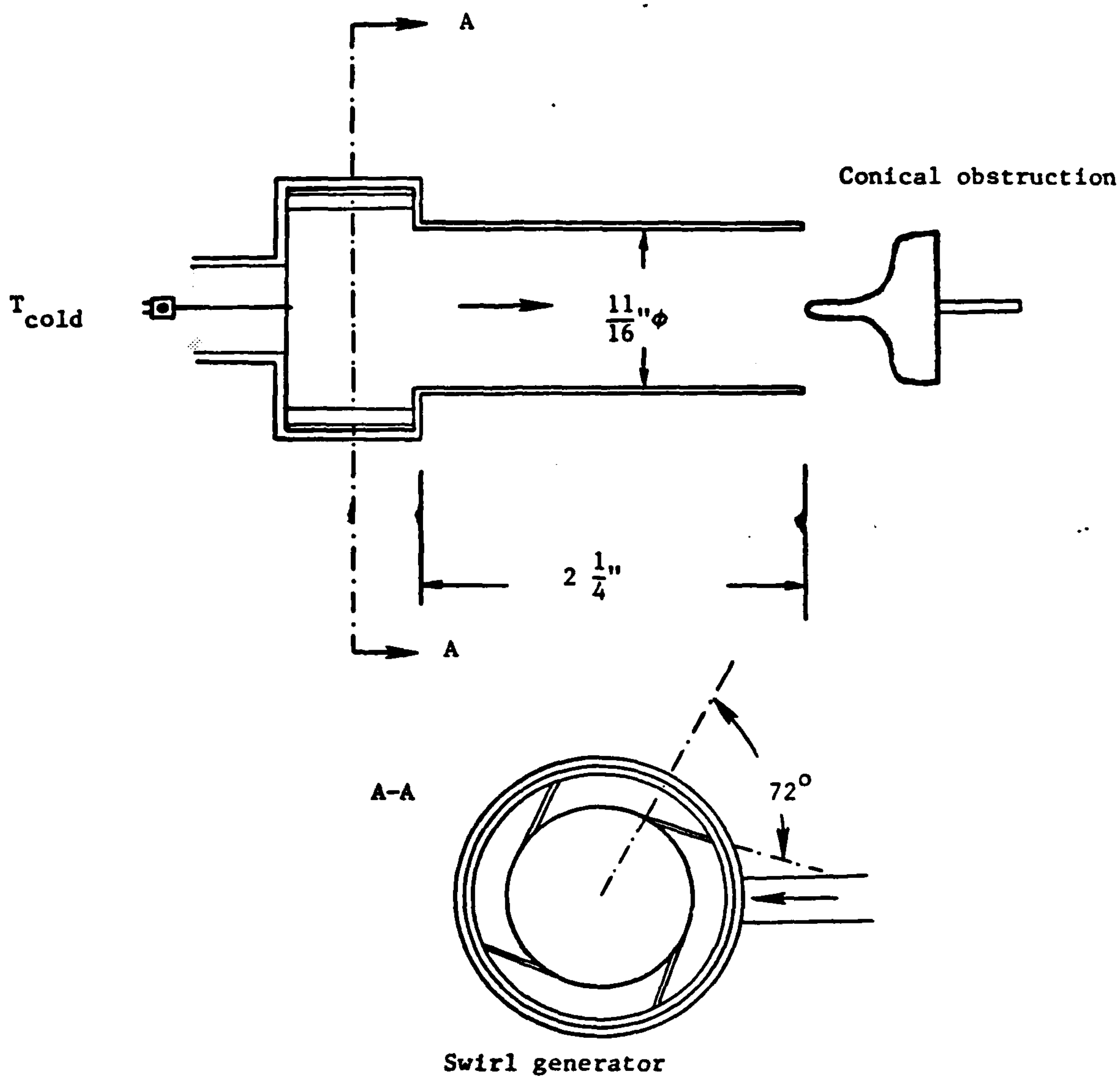

A
Conical obstruction
T_{cold}
$\frac{11}{16}$"ϕ
2 $\frac{1}{4}$"
A
A-A
72°
Swirl generator

FIGURE 4

blocking the original cold end, the air discharges only from one end, the one which used to be the hot end: this change to a uni-flow configuration, which corresponds to the model flow adopted in the analysis, was made in order to ease a direct comparison with the theoretical prediction. With the length of the main pipe thus shortened, it was found that the provision of the flow controlling valve interfers seriously with the intensity of the vortex whistle. Since the rig was eventually to be further modified to attenuate the vortex whistle by the installation of acoustic suppressors, it was necessary to minimuze the acoustic interference in this present baseline configuration -- and at the same time prevent the entrainmentof the ambient air into the test section, which otherwise would occur due to the lowered pressure at the core of the vortex. To meet these conflicting requirements, several configurations of conical shapes were tried and among these, a shape shown in Figure 4 was finally selected.

A Chromel-Alumel thermocouple of $\frac{1}{16}$" diameter, placed flush with the surface of the cold end block made of teflon, monitors the temperature at the centerline of the tube (designated as T_{cold}), and the measured data is shown in Figure 5. The radial distribution of temperature, Figure 6, was taken at an axial position of 1 $\frac{1}{8}$" from the manifold by traversing a thermocouple through a port provided on the wall of the main tube. Both Figures 5 and 6 serve to confirm the point that the modification to uni-flow type with shortened tube length still preserves the temperature separation in the radial direction.

The dependence of the first and second harmonics of the vortex whistle due to change in the inlet pressure is shown in Figure 7, its $\frac{1}{3}$ octave frequency spectra in Figure 8. Notice once again the predominance of the first

Test #454

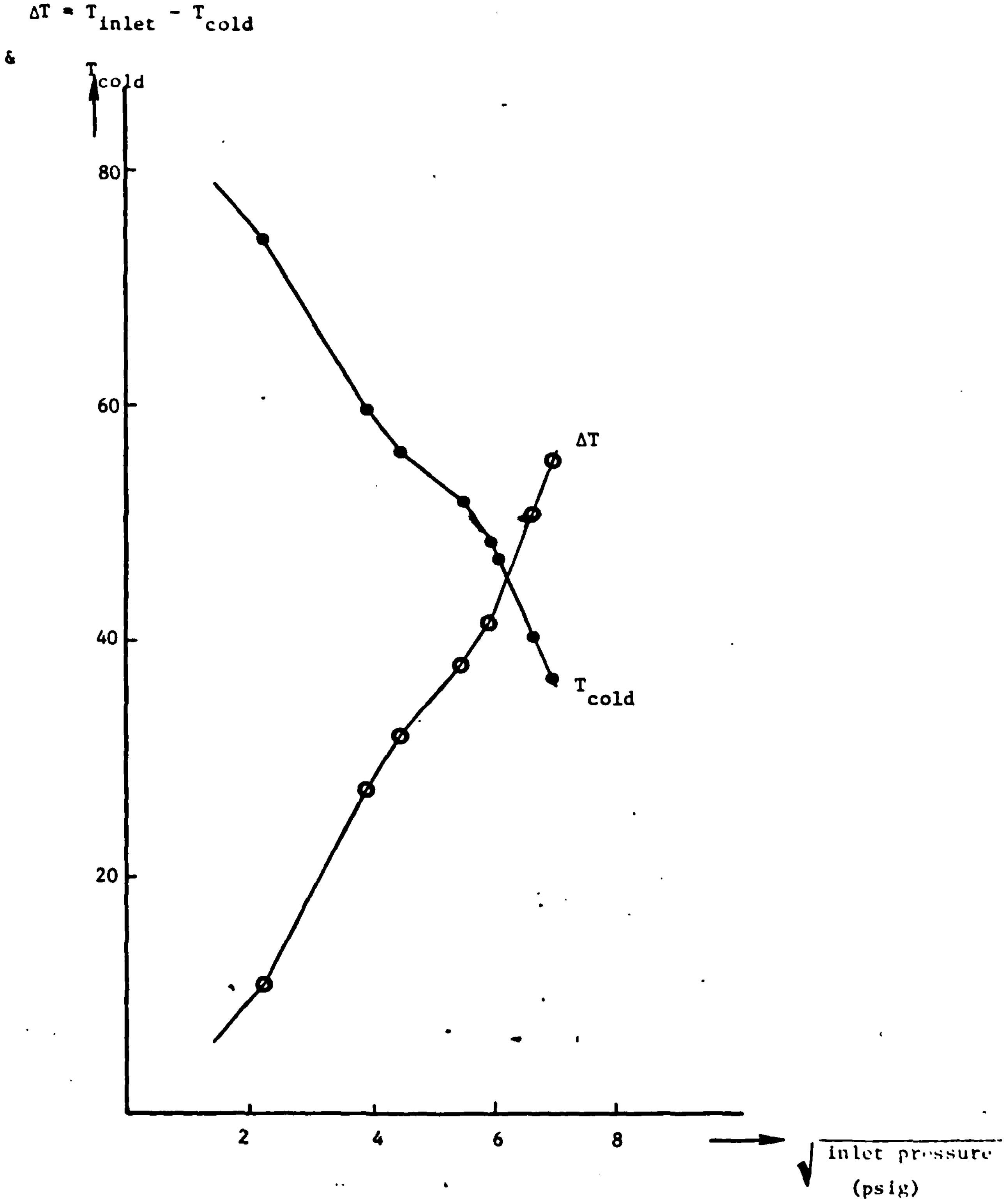


FIGURE 5

RADIAL TRAVERSE OF TEMPERATURE

Test #117

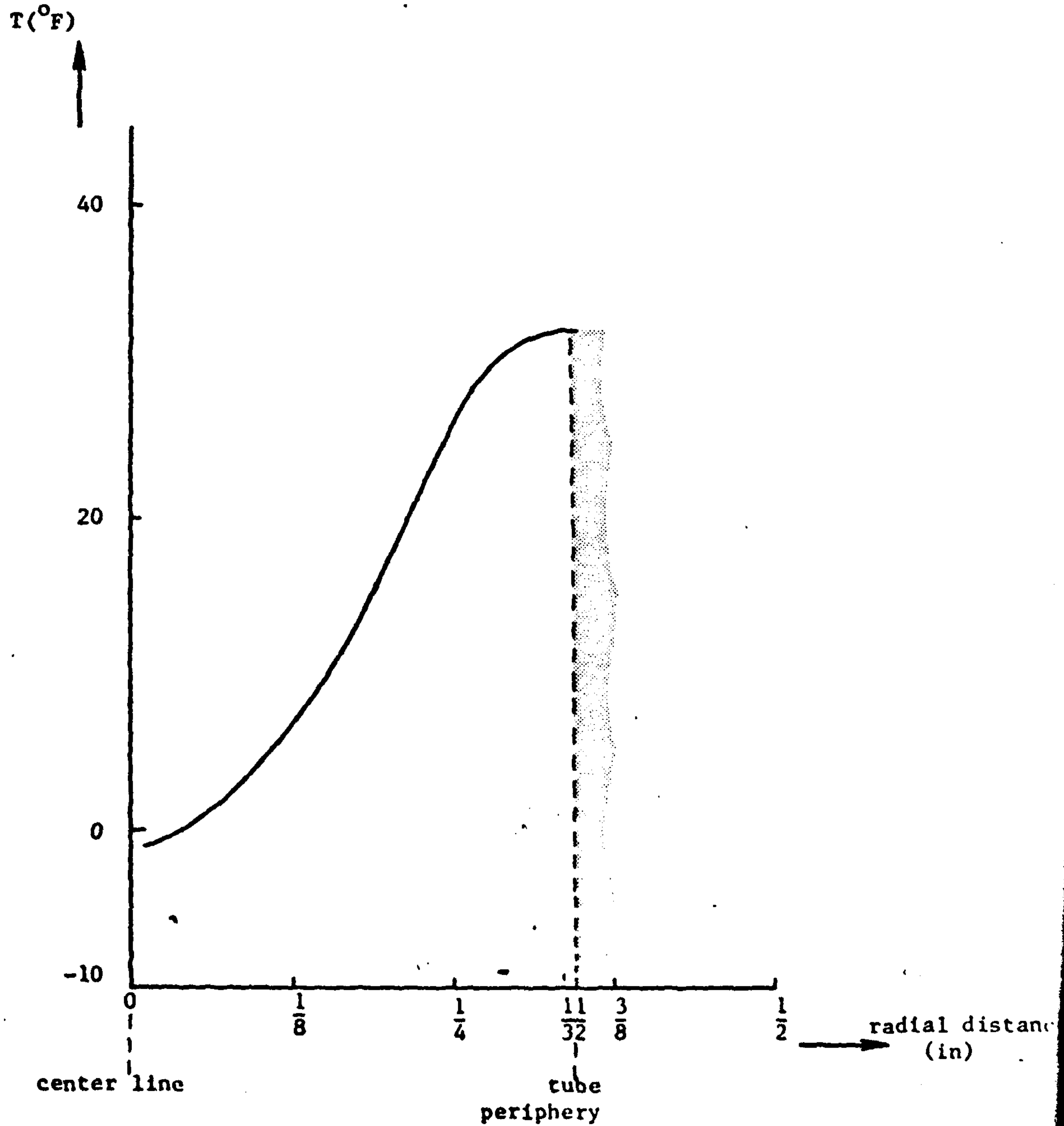


FIGURE 6

Test #454

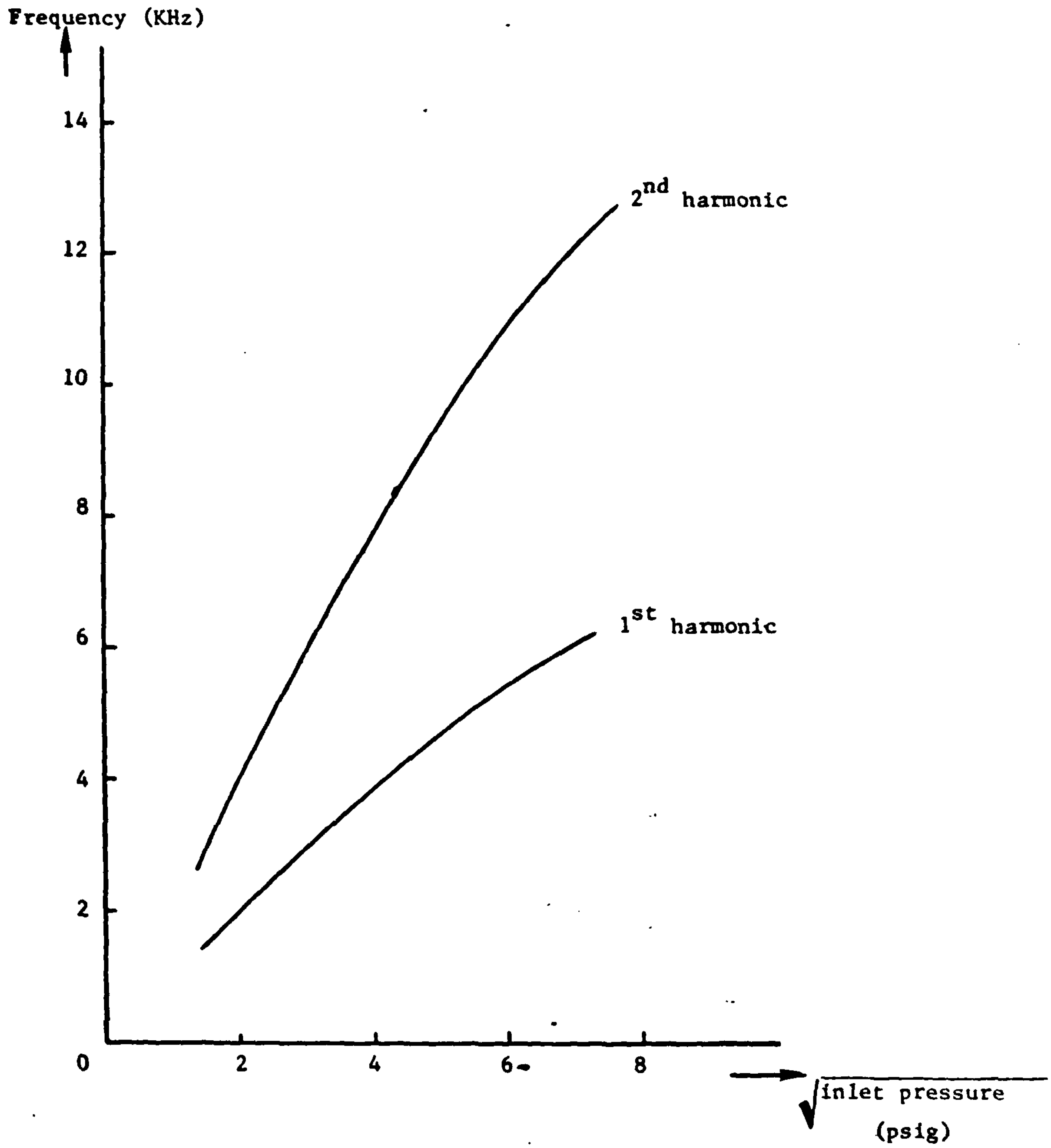


FIGURE 7

Test #454

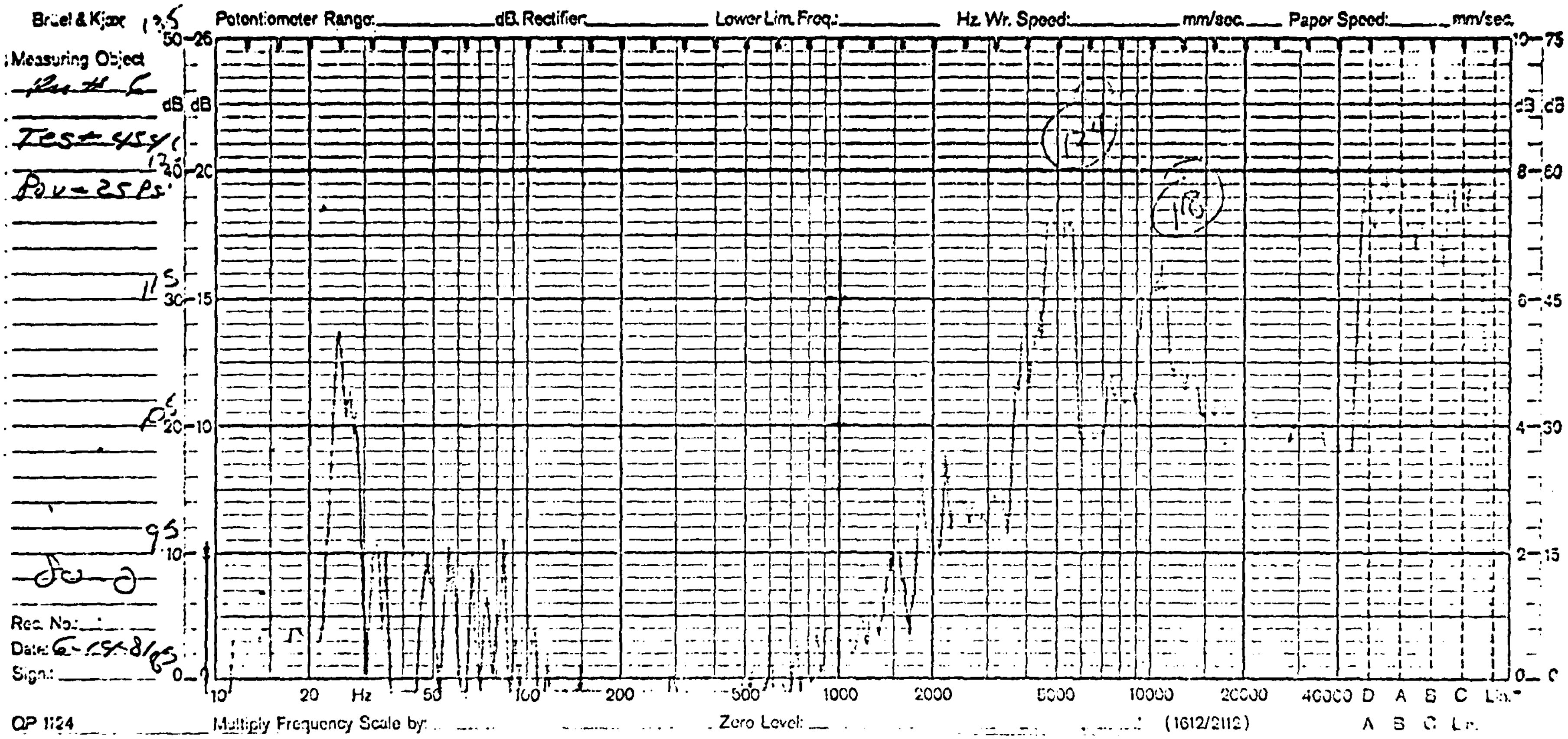


FIGURE 8

harmonic and another conspicuous peak of the second harmonic, though the decibel level of the latter is less than the former.

According to our theory previously developed, the first harmonic is described as

$$u' = \bar{u}(r) \cos (m\phi - \omega t + kz)$$

where the meaning of the notation is explained in Ref. 17. The present experiment determined that the wave number on the first harmonic, m, is 1. This was achieved by placing two microphones at different circumferential positions on the exit plane of the main tube and measuring their phase difference (ψ). After filtering only the frequency of the first harmonic, for two microphones placed 180° apart, ψ was found to be $\psi = 180^{\circ}$; when they were 90° apart, $\psi = 90^{\circ}$; this implies $m = 1$. Our analysis predicts that for $m = 1$ wave, the acoustic streaming near the tube periphery becomes exceedingly large; in other words, the significant amount of total temperature separation in the radial direction should occur if and when a periodic disturbance with such a wave number as $m = 1$ is present. Thus, the confirmation of the vortex whistle to be $m = 1$ type when the Ranque-Hilsch effect exists is crucially important in suggesting a likelihood that the vortex whistle is indeed a mechanism for the temperature separation.

As for the second harmonic, our analysis further predicts that the first harmonic beget the second harmonic, through nonlinear convective terms of the equation of motion. Thus corresponding to the following form of the first harmonic,

$$u = \bar{u}(r) \cos (\phi - \omega t + kz) \quad ,$$

consider, for example, the term like

$$u' \frac{\partial u}{\partial r} = \bar{u}(r) \frac{d\bar{u}(r)}{dr} \cos (\phi - \omega t + kz) \cdot \cos (\phi - \omega t + kz)$$

$$= \bar{u}(r) \frac{d\bar{u}(r)}{dr} \frac{1 + \overbrace{\cos (2\phi - 2\omega t + 2kz)}^{\text{second harmonics}}}{2} \qquad (1)$$

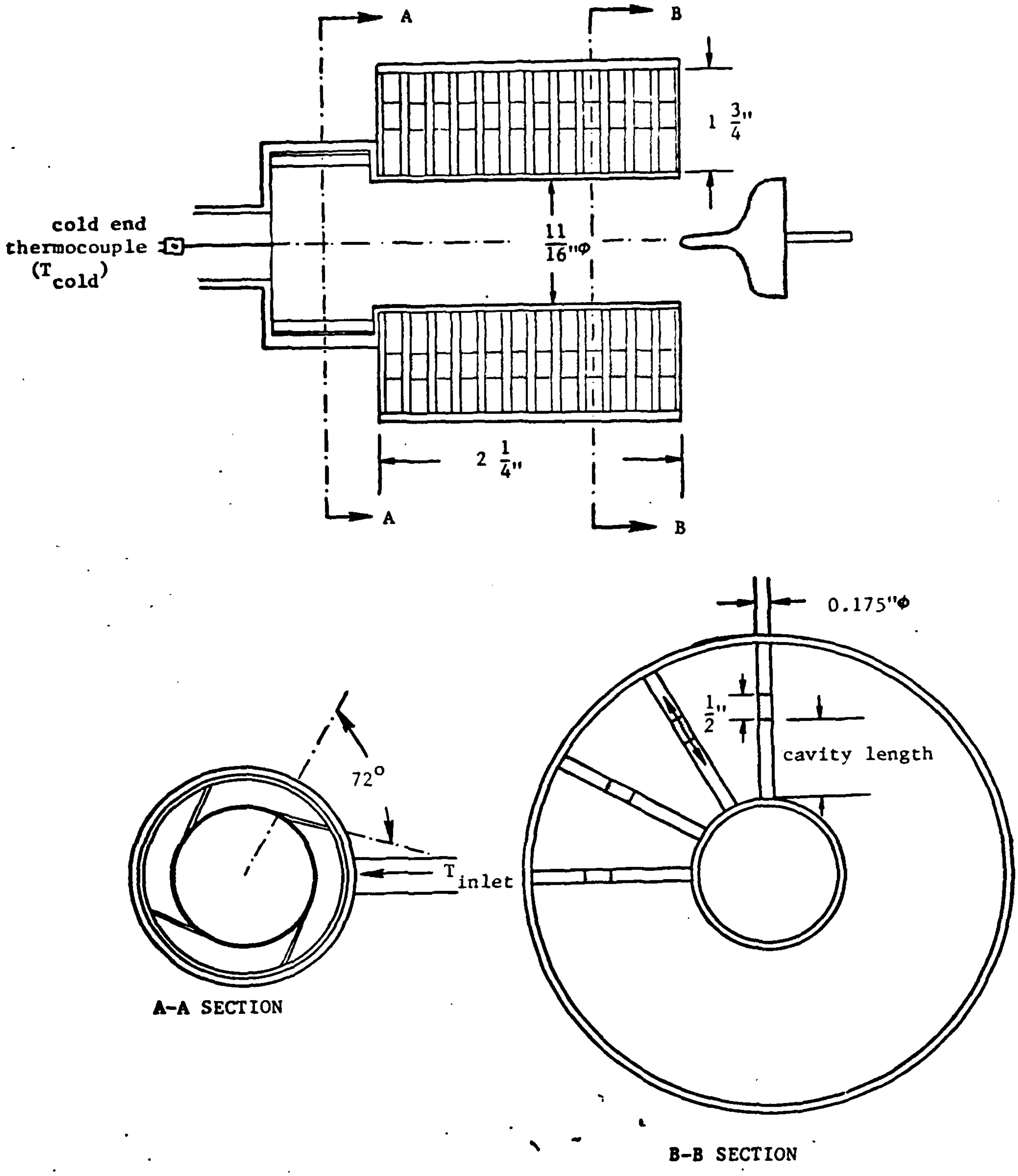
This implies that the wave number of the second harmonic should be 2. This was also confirmed in the same way as the one for the first harmonic; that is, for two microphones placed 90° apart, the phase difference was now found to be 180°. Such existance of the second harmonic in the expected above form provides further additional support to our argument that the temperature separation is caused by the acoustic streaming. This is because the acoustic streaming is argued to be directly caused by the time average of the above nonlinear terms, which yields, when averaged temporarily the following d. c. component induced by unsteady disturbances:

$$\langle u' \frac{\partial u'}{\partial r} \rangle = \bar{u}(r) \frac{d\bar{u}(r)}{dr} \frac{1}{2} \qquad (2)$$

Therefore, if the temperature separation is caused by the acoustic streaming, it must always be accompanied by its mate of the unsteady part, consisting of the second harmonic given in the above form.

(B-3) INSTALLATION OF ACOUSTIC SUPPRESSORS

Upon the completion of the tests described above, where the wall surface of the main tube made of brass was smooth, it was replaced with a porous wall; this was surrounded by an intermediate teflon section (Figure 9), where acoustically tunable holes of 0.175" diameter, their numbers being 12 in the axial and 12 in the circumferential direction, were drilled out. By inserting plexiglass rods into each hole and adjusting its cavity length, variable from $1\frac{3}{4}$" to zero, vortex whistle at any desired frequency can be alternated. In order to reduce leakage, the intermediate teflon section is covered by a sheath of solid teflon. With regard to the porous holes on the main tube, corresponding to each hole of 0.175" in the teflon intermediate section, nine holes forming a circular pattern (Figure 10), with 0.025" diameter for eight holes and 0.020" for a center hole, were initially drilled out, although later all of the hole sizes were enlarged to 0.040".



A
B
1 3/4"
cold end
thermocouple
(T_{cold})
11/16"φ
2 1/4"
A
B
0.175"φ
1/2"
cavity length
72°
T_{inlet}
A-A SECTION
B-B SECTION

FIGURE 9

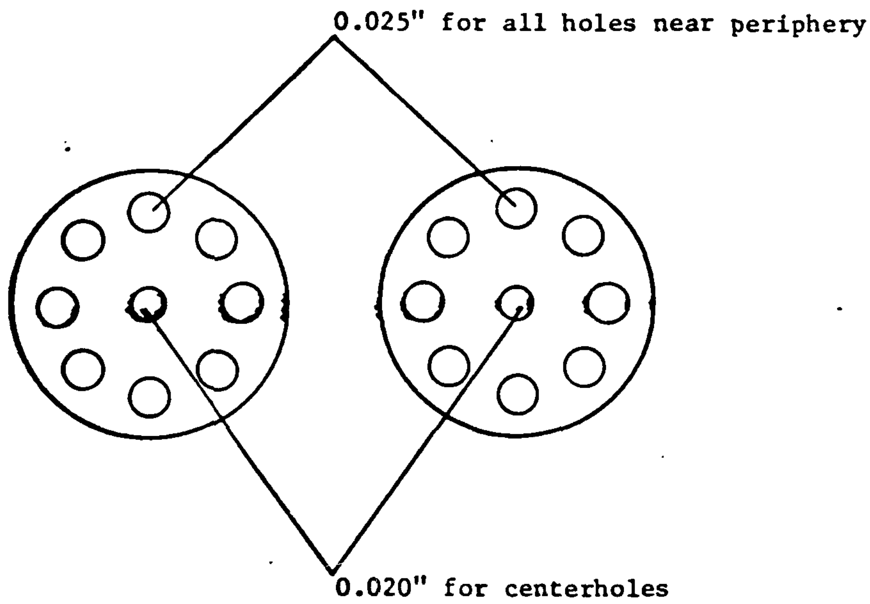


FIGURE 10

To ensure that the modification of main tube from a smooth wall to a porous one does not significantly alter the temperature separation and characteristics of the vortex whistle, initially a test was performed with all cavity lengths set to zero. The measured frequency, Figure 11, shows the slight decrease, as might be expected from the slow-down of swirl due to the presence of porous wall. Except for this, the frequency spectra (Figure 12) and temperature separation (Figure 13) remains virtually the same as the smooth wall; thus, the change to a porous wall did not inadvertently alter the main characteristics.

Now, as is well known, the working principle of this organ type acoustic suppressor is as follows: by selecting the cavity length equal to a quarter wave length and thereby forcing the loop portion of the standing wave within the cavity to be in contact with the porous surface, one can disrupt and reduce the magnitude of unsteady disturbances at a desired frequency. Thus the cavity length, ℓ, is given by

$$\ell = \frac{1}{4} \frac{c}{f}$$

where c is the speed of sound, f, the frequency; this relationship is shown in Figure 14 as the broken line, while the solid line corresponds to the measured value for small holes on the main tube, the method to determine this to be discussed later.

When at a certain cavity length, the vortex whistle with a corresponding frequency is attenuated, our analysis predicts that the amount of temperature separation in the radial direction should decrease. Thus, for example, the temperature at the surface of cold end block should rise and the data indeed verify this. In examining Figure 15, 16 and 19, when $\Delta T = T_{inlet} - T_{cold}$

ZERO CAVITY (Test #449)

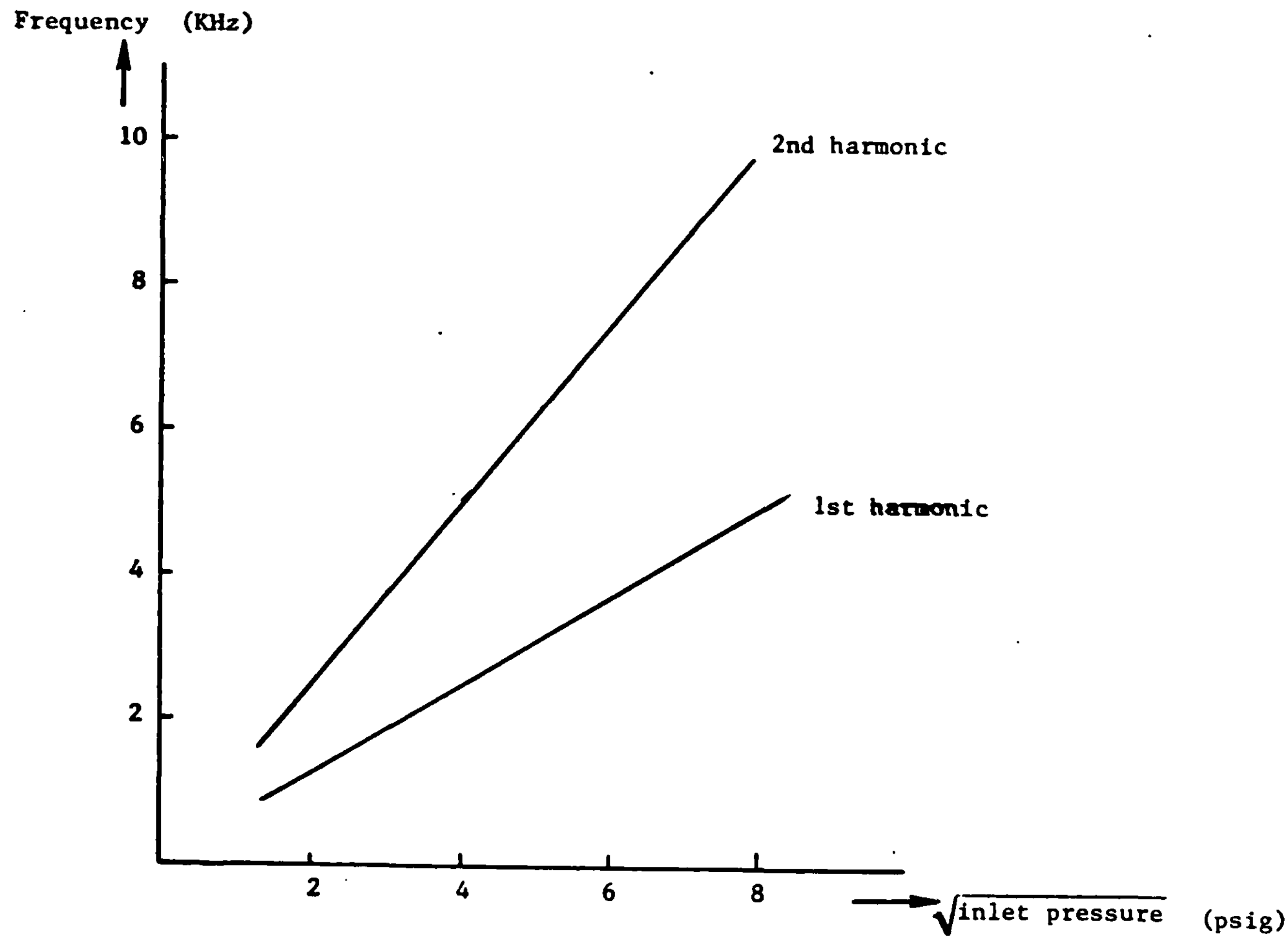


FIGURE 11

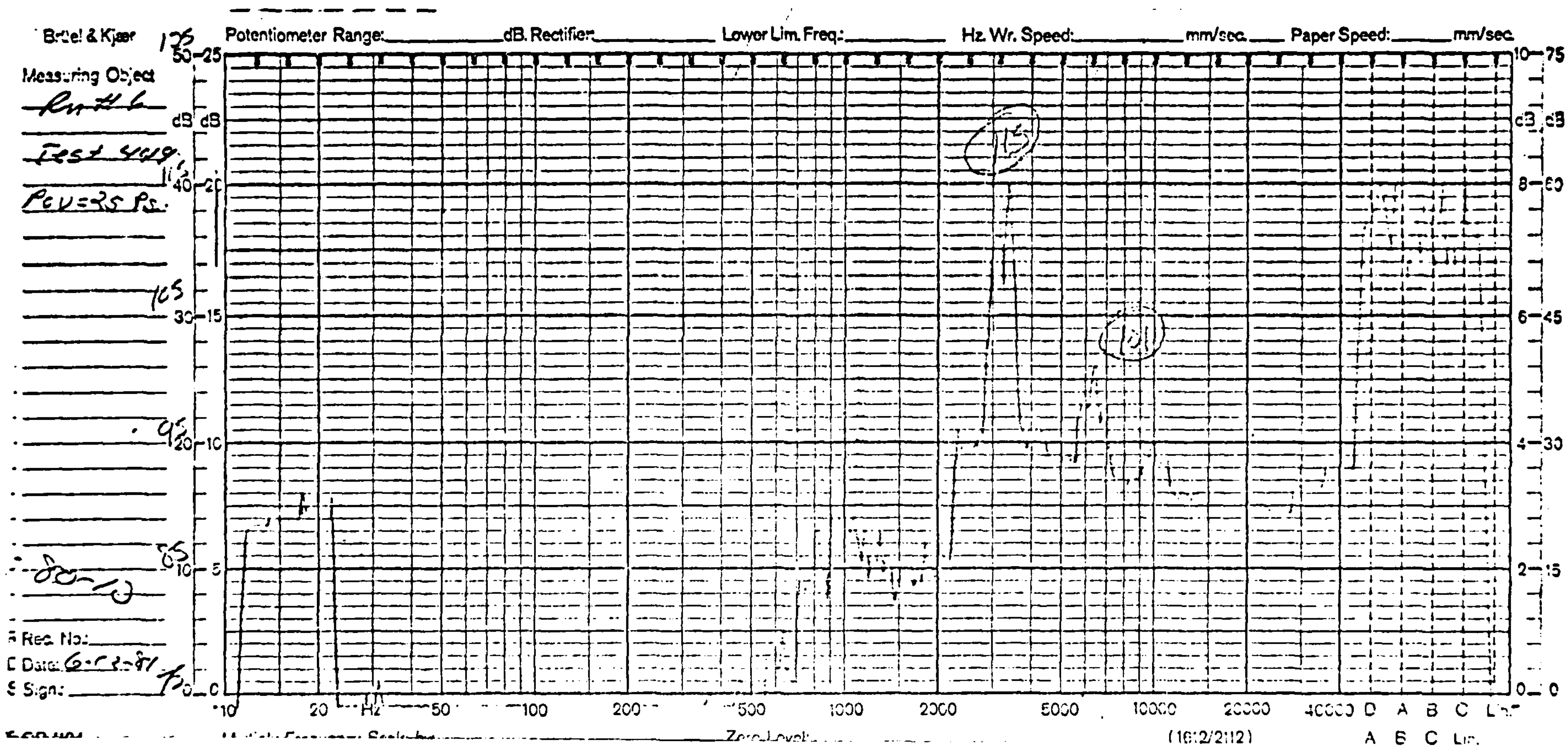

Brüel & Kjær
Potentiometer Range:
dB. Rectifier:
Lower Lim. Freq.:
Hz. Wr. Speed:
mm/sec.
Paper Speed:
mm/sec.
Measuring Object
Test 449
Rec. No.:
Date: 6-23-81
Sign.:
dB
10
20
50
100
200
500
1000
2000
5000
10000
20000
40000
D
A
B
C
Lin.
(1612/2112)

FIGURE 12

Test #449

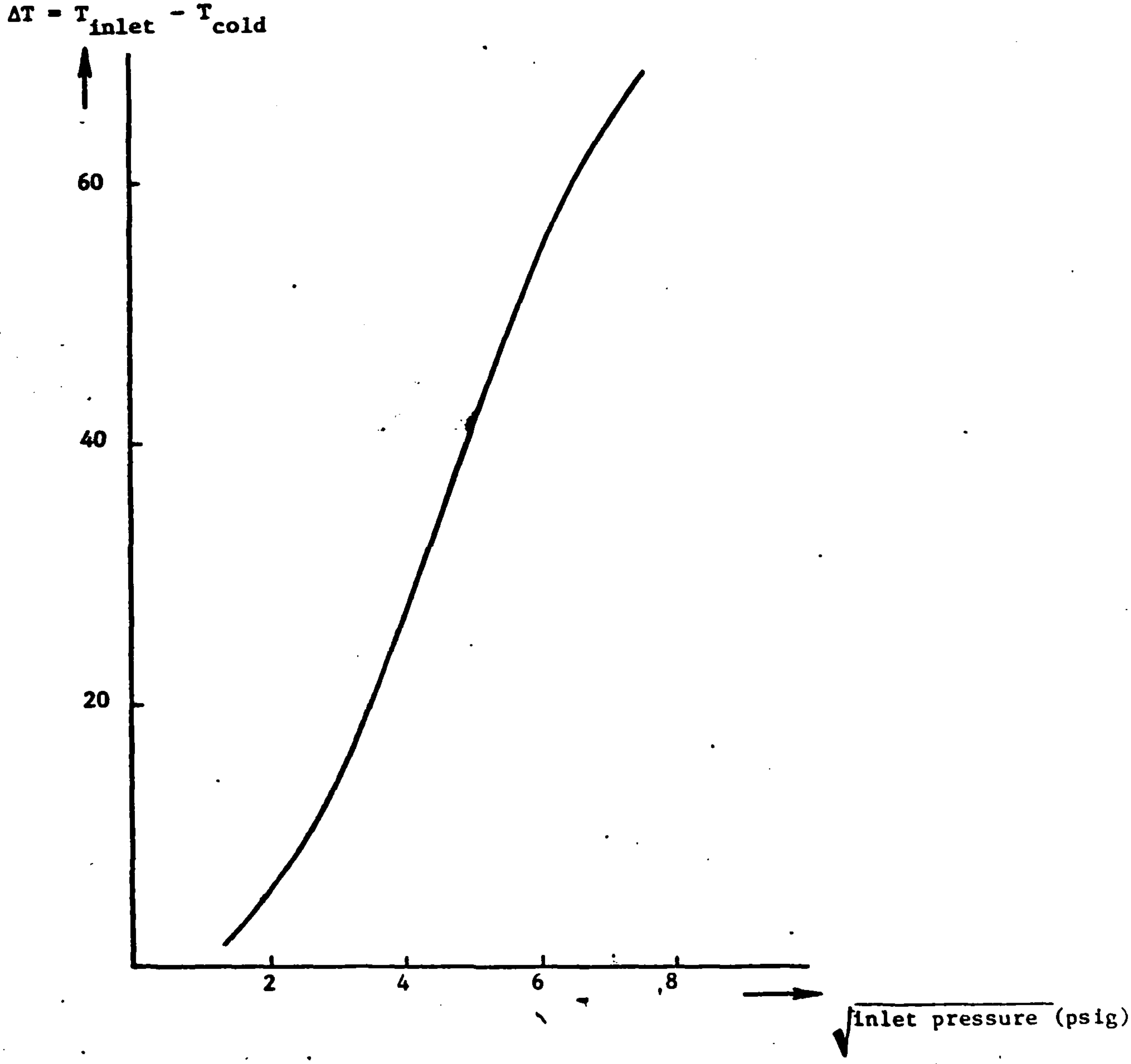


FIGURE 13

TUNED FREQUENCY AND CAVITY LENGTH

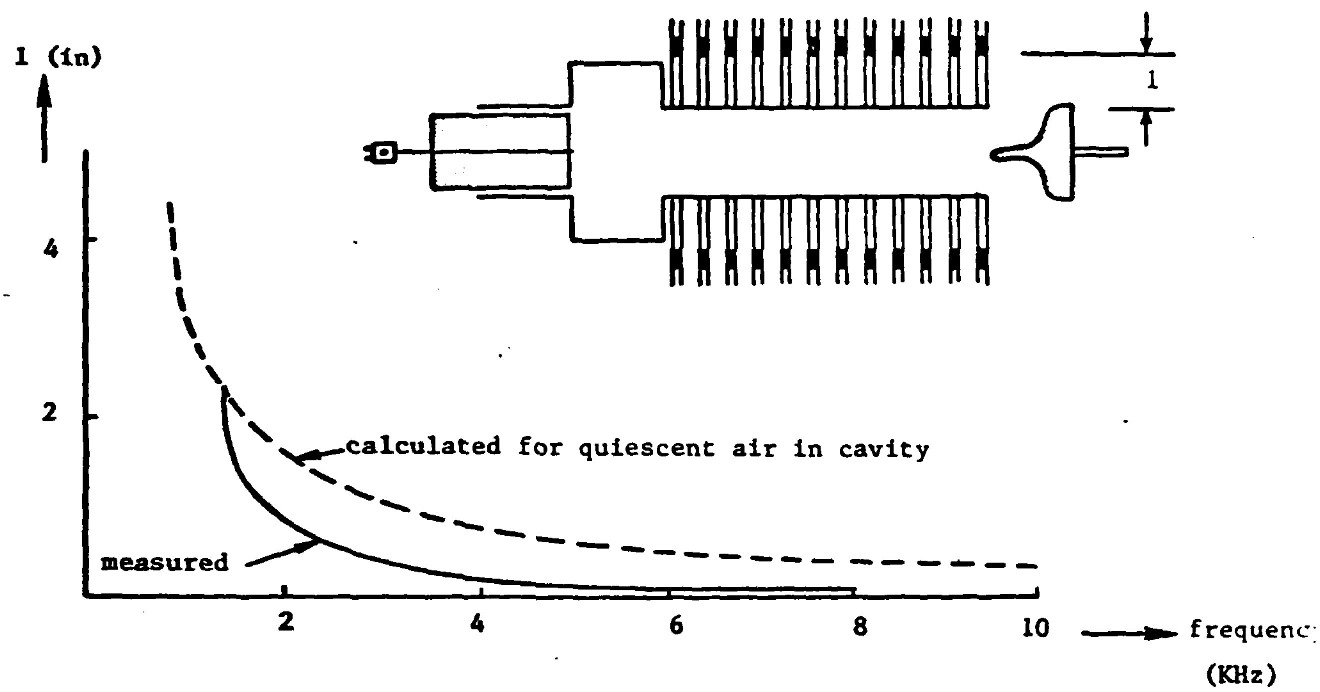


FIGURE 14

is plotted instead of cold end block temperature, T_{cold}, itself, it has to be borne in mind that any increase of T_{cold} would appear as decrease in ΔT representation.

(B-4) *THE ACOUSTIC SUPPRESSOR DATA WITH SMALL HOLES ON THE MAIN TUBE*

We first present the results where the holes on the main tube are small, 0.025" diameter for eight holes and 0.020" for a centerhole. In Figure 15 (a), where the cavity length is set equal to 0.8", as the first harmonic of the vortex whistle reaches around 2000 Hz, all of a sudden, the sound level becomes audibly quieter, as seen from the reduction of decibels of both the first and second harmonics; this is accompanied by the abrupt drop of ΔT at the corresponding frequency. Even for the other cavity lengths, this drop in ΔT takes place so instaneously; hence it is convenient to define the corresponding first harmonic frequency as the tuning frequency, shown already as a solid line in Figure 14. As the inlet pressure is further increased above this tuning frequency, the narrow band frequency analyzer reveals that the sharp peak of the first and second harmonics become less spiky, changing into a form resembling a mountain range spread over a certain band width of frequency; this is shown as a vertical line of frequency in the figure. Although the drop in ΔT is only $1^{o}F$ due to slight reduction in db, nonetheless the data reveals not only the direct link between the vortex whistle and temperature separation but also discloses the following important point: when one reduces the amplitude of the first harmonic, to which the cavity length is nominally tuned, the second harmonic is also attenuated. This implies, once again, that the second harmonic is induced by the first harmonic.

Since according to our theory, the steady part associated with the second harmonic causes the temperature separation, one might expect to gain increased drop in ΔT by tuning, in addition to the frequency of the first harmonic, to the frequency of the second harmonic, thereby reducing the amplitude of its

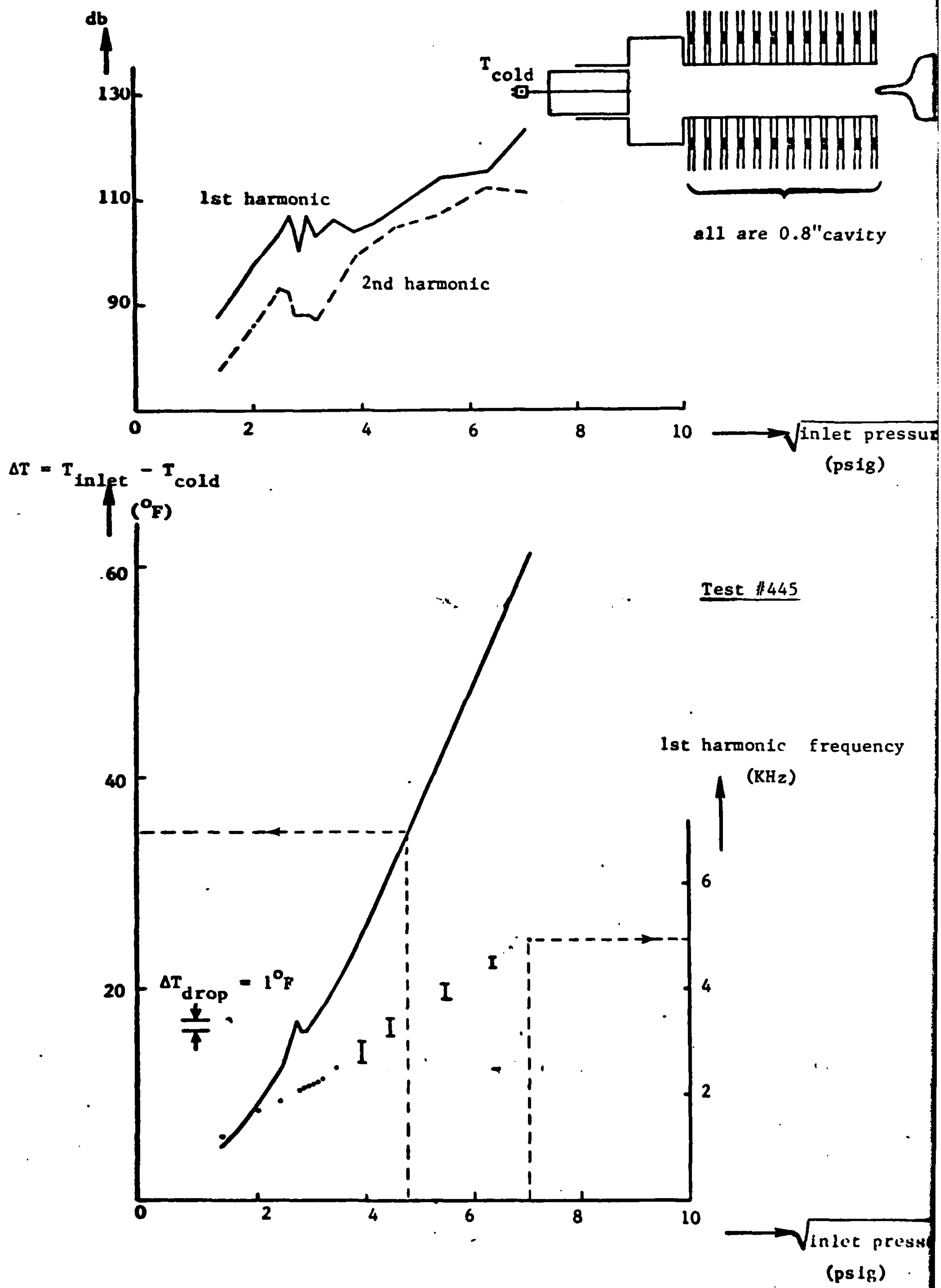

db
130
110
90
1st harmonic
2nd harmonic
T cold
all are 0.8"cavity
0
2
4
6
8
10
√inlet pressu
(psig)
ΔT = T inlet - T cold
(°F)
60
40
20
Test #445
1st harmonic frequency
(KHz)
6
4
2
ΔT drop = 1°F
√inlet press
(psig)

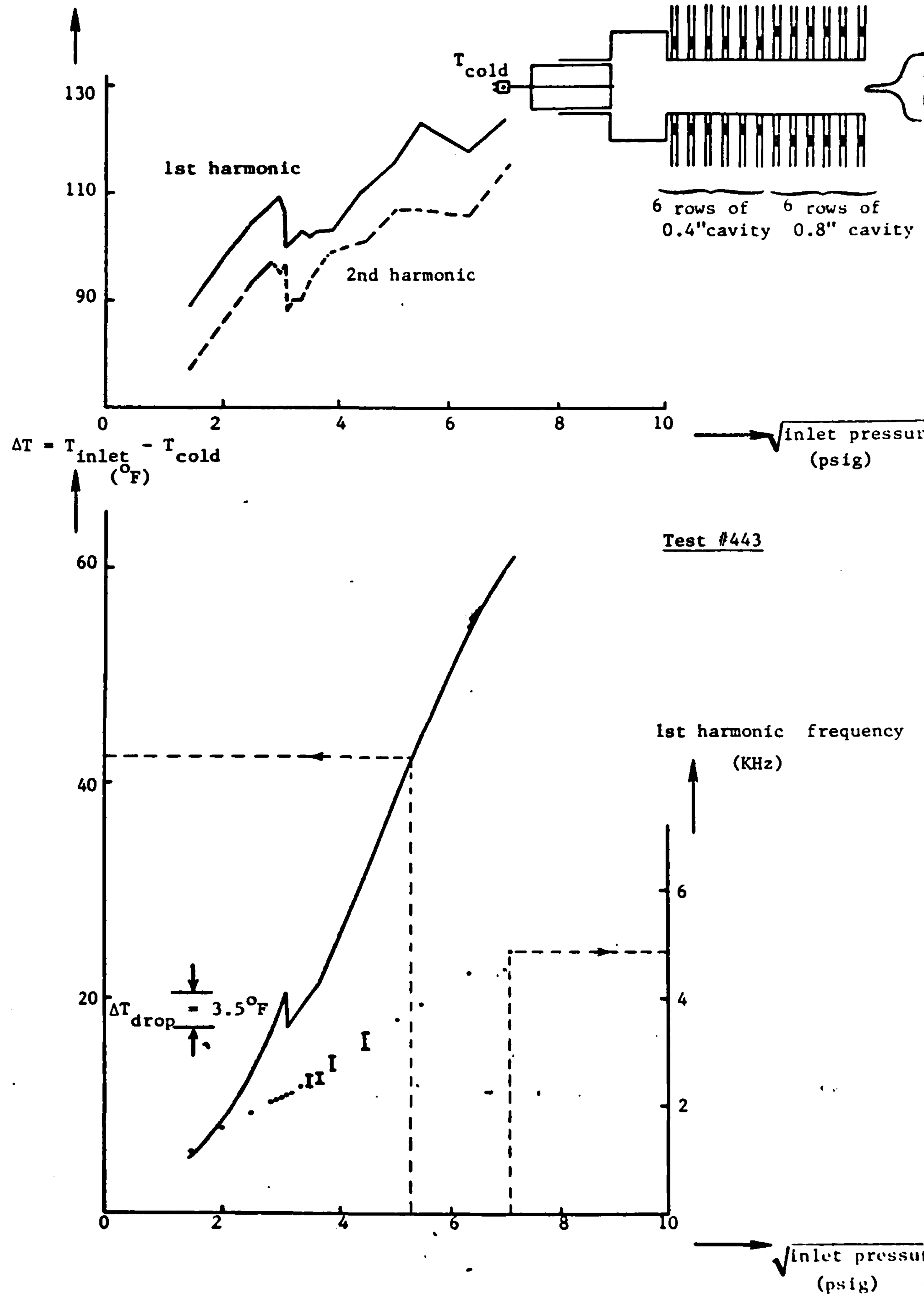
FIGURE 15 (a)

companion, the steady part (see Equation (1) and (2). Figure 15 (b)shows that this is in fact the case; there, for the six rows of tuning holes near the manifold, the cavity length is reduced to 0.4", corresponding to the tuning frequency of the second harmonic, while for the six rows near the open end, the cavity length is still 0.8", corresponding to the first harmonic. Notice that now a drop in ΔT is increased to $3.5^{\circ}F$ and, at the same time, the corresponding plunge in sound level becomes deeper, particularly so for the second harmonic.

Figure 16 (a) and (b), where the primary cavity length is now set to 0.4", shows the data corresponding to Figure 15 (a) and (b); here the tuning frequency is now raised to 3000 Hz. Notice once again the increase of ΔT drop when the cavity length is tuned to both the first and second harmonics (Figure 16 (b)). However, by far the largest drop in ΔT is obtained when, for 6 rows of tuning holes near the manifold, the cavity length is set equal to $1\frac{3}{4}$", as seen from Figure 16 (c), the drop in ΔT is $8.5^{\circ}F$. Although $1\frac{3}{4}$" coincides approximately equal to odd integer multiple of $\frac{1}{4}$ wave length of the second harmonic, which is equal to 0.2" (0.2" x 9 = 1.8") and thus one of its loop portions may possibly be affected, the reason why in this configuration, ΔT drop is the largest is not clear at present.

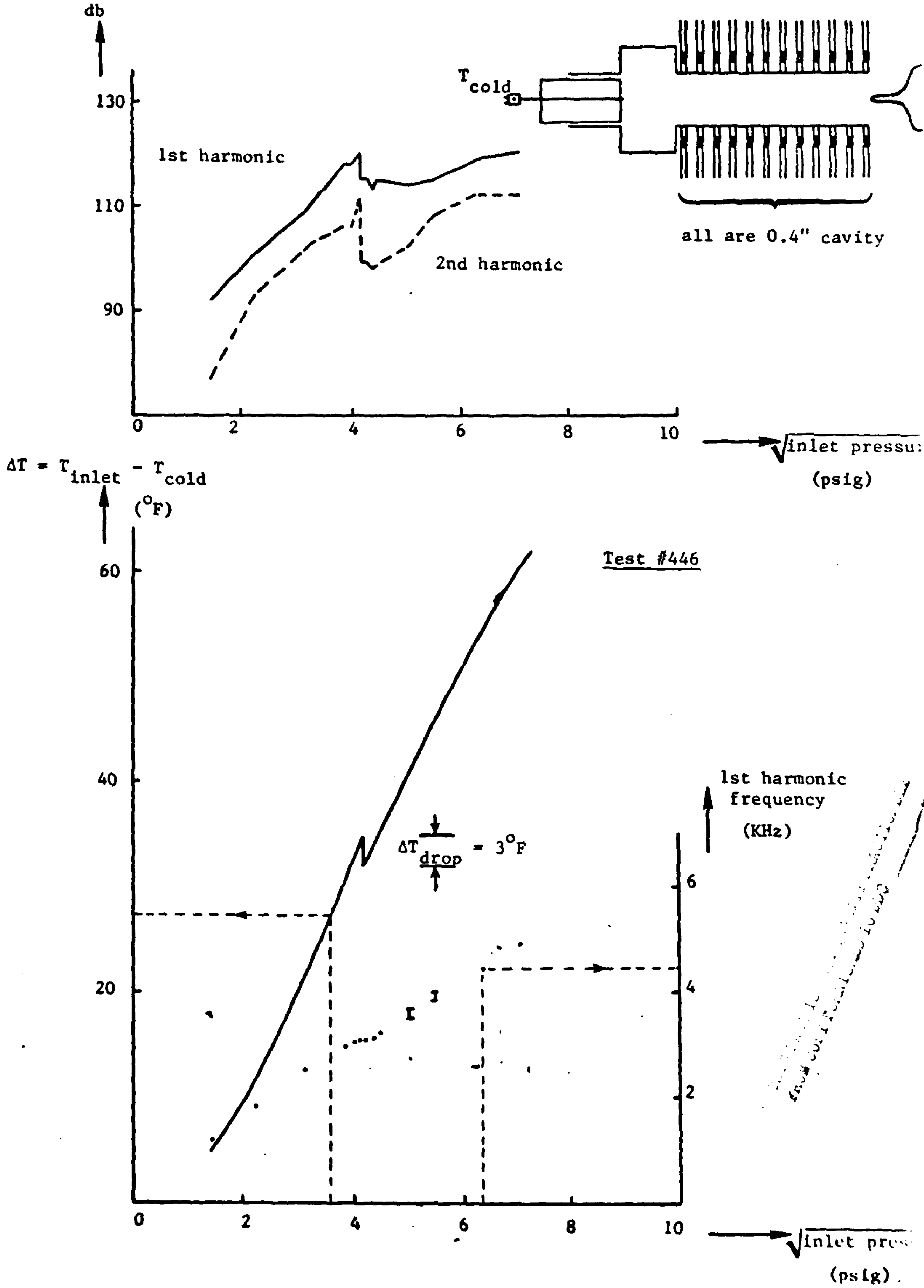
In Figure 15 and 16, the almost exact correspondence of ΔT drop with the matching plunge in decibel level confirms, beyond any doubt, the direct connection between the temperature separation and vortex whistle.

These experiments using the axially varying cavity length led us also to locate the source of the vortex whistle. Compare Figure 15 (b) and Figure 16 (d), where, in the former, for 6 axial rows of tuning holes near the open end, the cavity length is 0.8" and for the remainder of 6 rows near the manifold the cavity length is 0.4"; in the latter this axial arrangement is



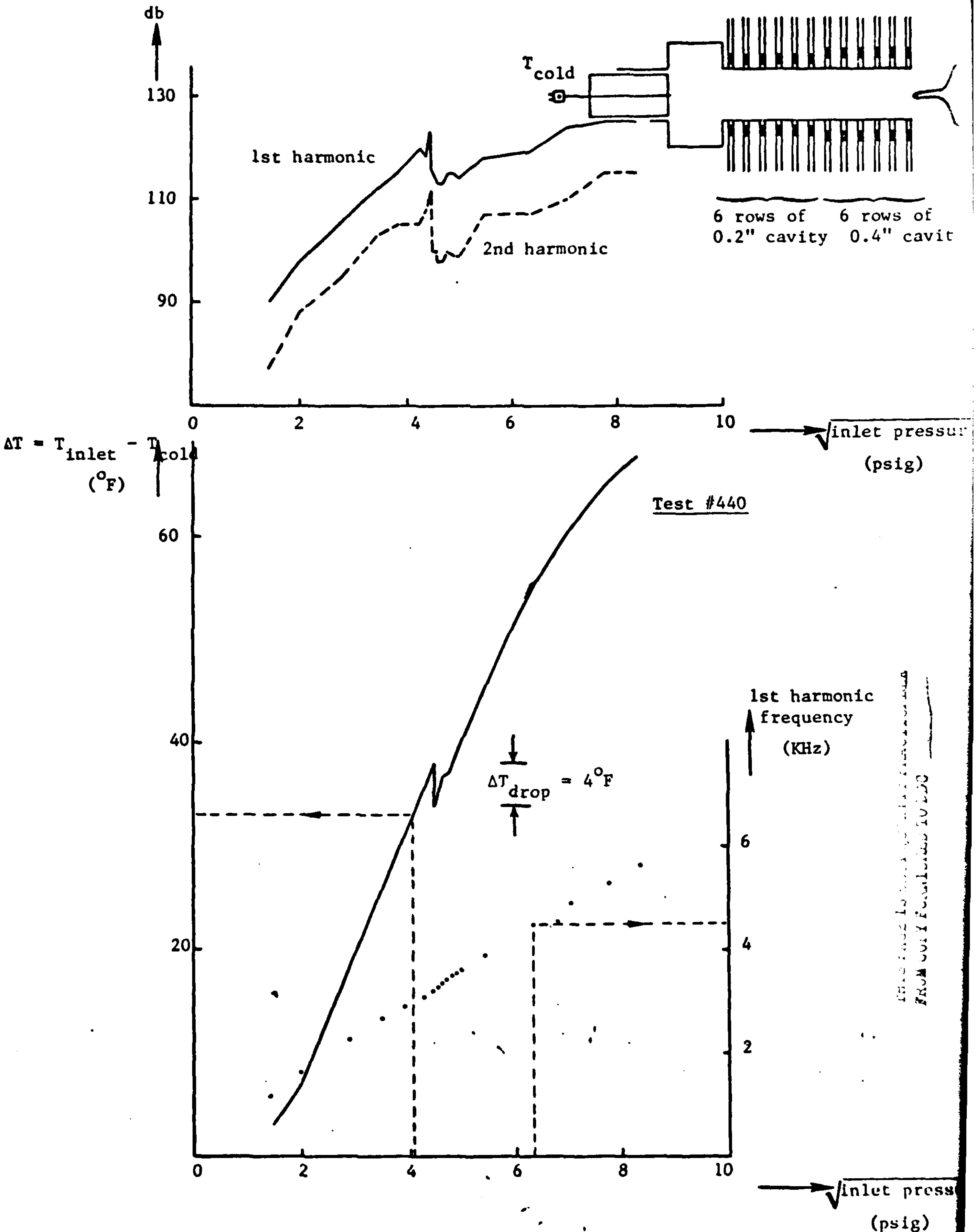
T cold
130
110
90
1st harmonic
2nd harmonic
6 rows of 0.4"cavity
6 rows of 0.8" cavity
0
2
4
6
8
10
√inlet pressure (psig)
ΔT = T inlet - T cold (°F)
Test #443
60
40
20
ΔT drop = 3.5°F
1st harmonic frequency (KHz)
6
4
2
√inlet pressure (psig)

FIGURE 15 (b)



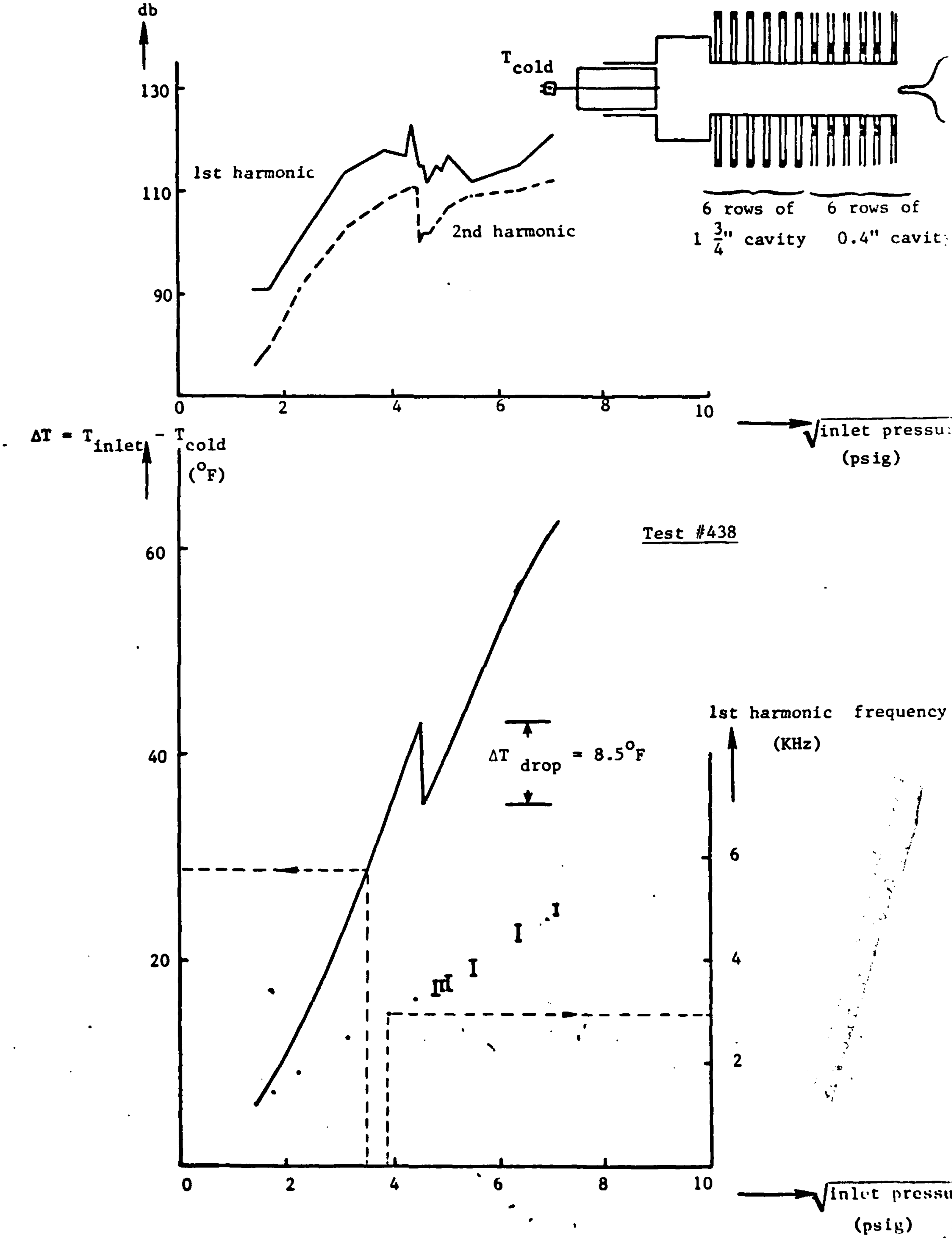
db
130
110
90
1st harmonic
2nd harmonic
T_{cold}
all are 0.4" cavity
0
2
4
6
8
10
$\sqrt{\text{inlet pressu:}}$
(psig)
$\Delta T = T_{inlet} - T_{cold}$
(^oF)
60
40
20
Test #446
$\Delta T_{drop} = 3^oF$
1st harmonic
frequency
(KHz)
6
4
2
0
2
4
6
8
10
$\sqrt{\text{inlet pre}}$
(psig)

FIGURE 16 (a)



db
130
110
90
1st harmonic
2nd harmonic
T cold
6 rows of 0.2" cavity
6 rows of 0.4" cavit
0
2
4
6
8
10
√inlet pressur (psig)
ΔT = T inlet - T cold (°F)
Test #440
60
40
20
ΔT drop = 4°F
1st harmonic frequency (KHz)
6
4
2
√inlet press (psig)

FIGURE 16 (b)



db
130
110
90
1st harmonic
2nd harmonic
T cold
6 rows of 1 3/4" cavity
6 rows of 0.4" cavit
0
2
4
6
8
10
√inlet pressu
(psig)
ΔT = T inlet - T cold
(°F)
Test #438
60
40
20
ΔT drop = 8.5°F
1st harmonic frequency
(KHz)
6
4
2
0
2
4
6
8
10
√inlet pressu
(psig)

FIGURE 16 (c)

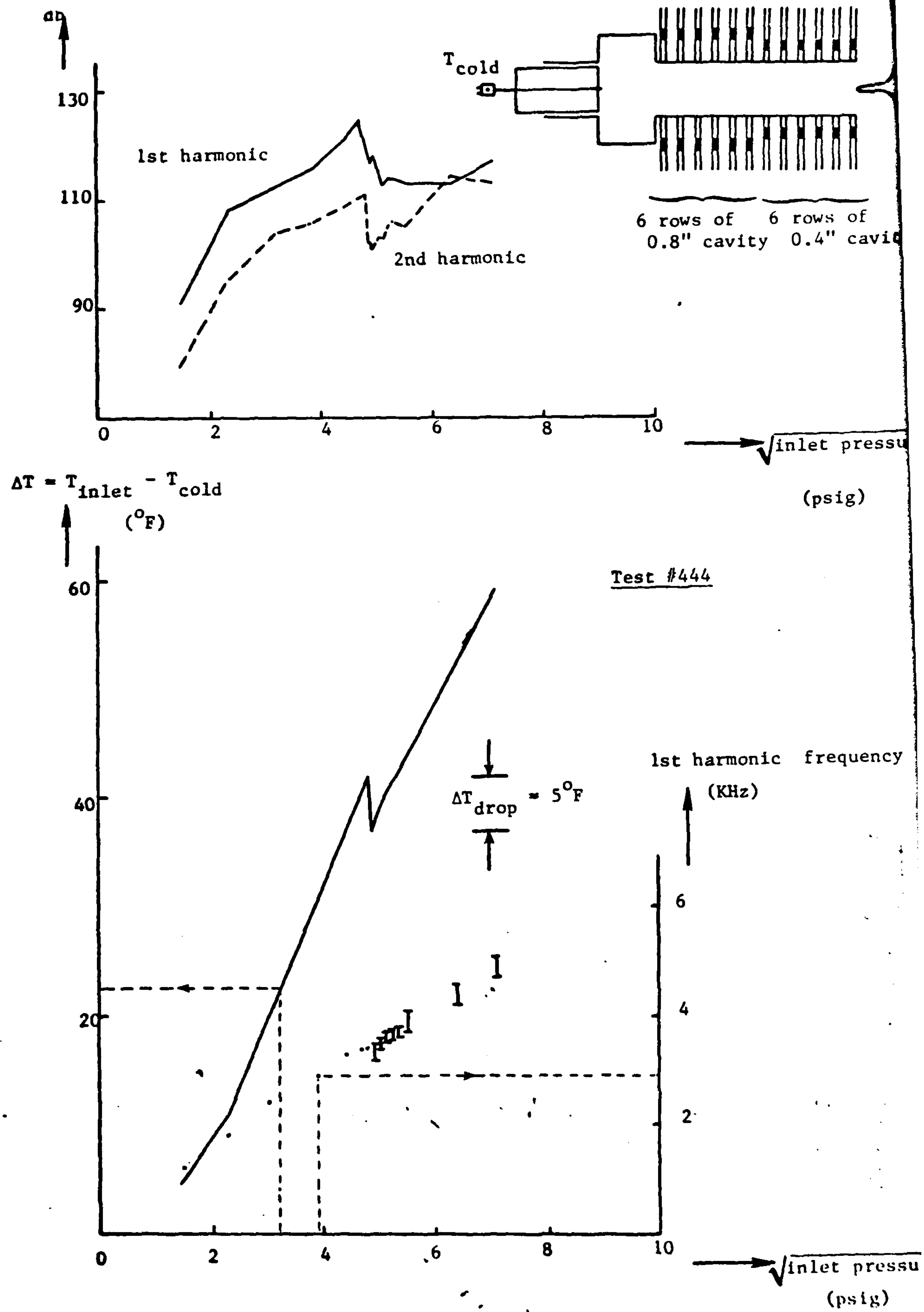

db
130
110
90
1st harmonic
2nd harmonic
T cold
6 rows of 0.8" cavity
6 rows of 0.4" cavi
0
2
4
6
8
10
√inlet pressu
(psig)
ΔT = T inlet - T cold
(°F)
Test #444
60
40
20
ΔT drop = 5°F
1st harmonic frequency
(KHz)
6
4
2
0
2
4
6
8
10
√inlet pressu
(psig)

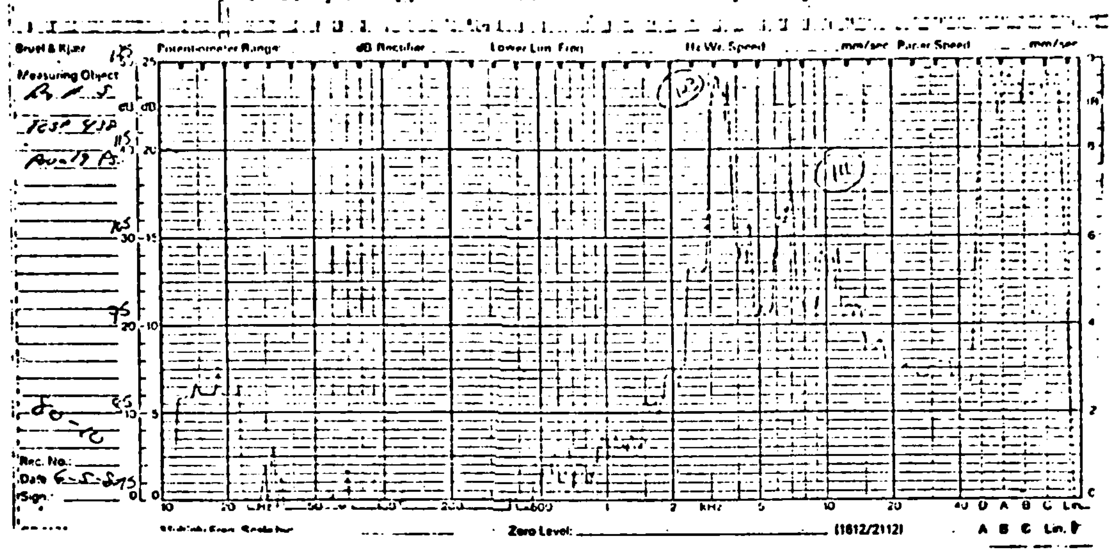
FIGURE 16 (d)

reversed. Observe that the tuning frequency of Figure 15 (b) corresponds to 0.8", while in Figure 16 (d), the tuning frequency corresponds to 0.4"; in other words, the tuning frequency corresponds only to the cavity length near the open end and not to the one near the manifold. The implication of this is that the excitation source of the vortex whistle seems to lie near the vicinity of the open end.

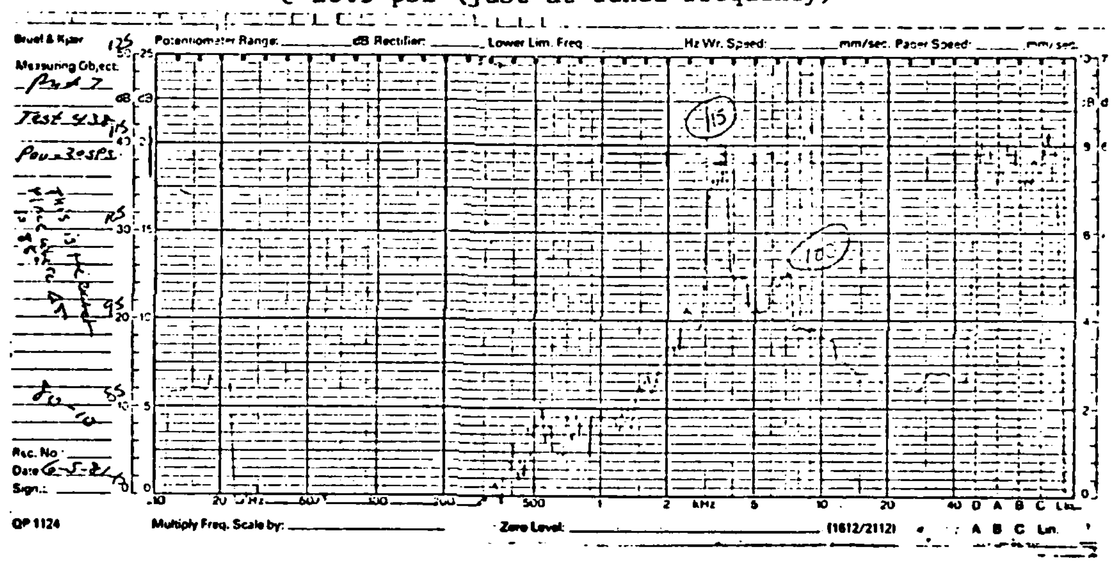
Throughout the above data, even at the tuned condition, both the first and second harmonics still retain distinctive spiky peaks, as seen from the frequency spectra of Figure 17, which corresponds to the case of maximum drop in ΔT, Figure 16 (c). Thus in them, the vortex whistle is far from being substantially suppressed; to the contrary, the magnitude is reduced only by 10db or so and this leaves room for further drop in ΔT by achieving greater reduction in sound level. However, as already pointed out, the precipitous drop in both temperature and sound level observed for these small holes on the main pipe --- 8 holes of 0.025" diameter and a center hole of 0.020" --- verify that the temperature separation is indeed related to the vortex whistle. In order to obtain the steep drop so as to substantiate the above point, it was necessary to use these small sized holes; the data with larger sized holes, to be discussed next, show the across-the-board reduction in decibels, the sound level at all the frequencies being affected. In a figurative sense, the impression is as if, with tiny holes on the wall surface of the main pipe, one can 'fool' the air by leading it up to the brink of the tuning frequency without letting it 'smell' the presence of the cavity until at the tuning frequency, it suddenly finds the tuning cavity and falls precipitously. It was found that the most favorable arrangement to achieve the sudden drop is not the one shown in Figure 10, where the cavity holes match with the circular pattern of holes on the main tube in a nominal fashion, but, for the reason

Test No. 438

@ 19 psi (just before tuned frequency)



@ 20.5 psi (just at tuned frequency)



@ 50 psi (out of tuned frequency)

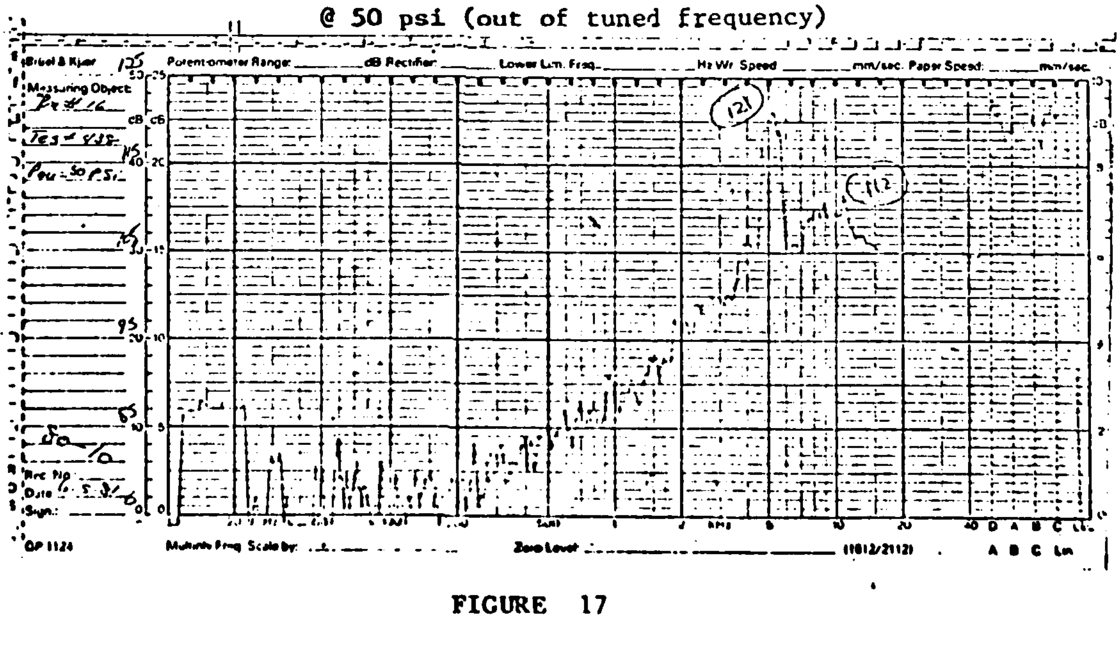


FIGURE 17

not clear, the one where the relative position between the cavity and tube holes are slightly misaligned, as seen in Figure 18, so that some of the tube holes sit on the periphery of the cavity.

(B-5) *THE ACOUSTIC SUPPRESSOR DATA WITH LARGER HOLES ON THE MAIN TUBE*

Next the data where all the holes on the main tube are enlarged to the diameter of 0.040" will be presented (Figure 19). Figure 20 shows the comparison of th larger hole data at $1\frac{3}{4}$" cavity with that of zero cavity. One observes that both the sound level and temperature separation, ΔT, are considerably lower and such reduction takes place over all the measured range of frequency. The frequency spectra for $1\frac{3}{4}$" cavity are presented in Figure 21, where at 15 psi of inlet pressure, the vortex whistle loses its distinctive characteristics of dominant peak, as observed in comparison with the ones at 5 and 60 psi. This implies that the sound level is more attenuated in this range, resulting in approximately half of ΔT for zero cavity: for example, at 15 psi of inlet pressure, $\Delta T = 13^{\circ}$ for $1\frac{3}{4}$" cavity, while $\Delta T = 26^{\circ}$ for zero cavity. Although, when compared to zero cavity, ΔT is lower, the spectrum at 15 psi reveals that the first harmonic is still 93 db, the second harmonic 88 db; thus there exists room to reduce the sound further. Granted that even the more greater attenuation would not completely eliminate the temperature separation -- since, even in the absence of acoustic streaming, the total temperature in the core region of the vortex is lower due to dissipative effects -- nevertheless it is expected that additional reduction appears to be achieved.

Currently effort is under way to modify the main pipe and acoustic suppressors in order to further reduce the sound level; additionally, at the tuned condition, the radial traverse of temperature and a study on the effect of increased turbulence is being planned as a part of the phase II activities.

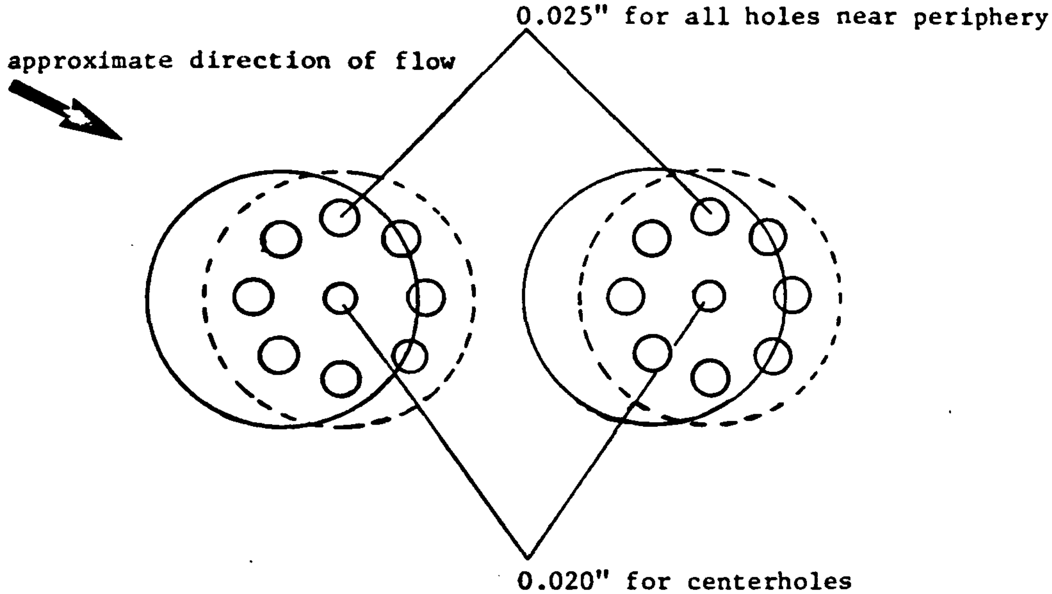

0.025" for all holes near periphery
approximate direction of flow
0.020" for centerholes

FIGURE 18

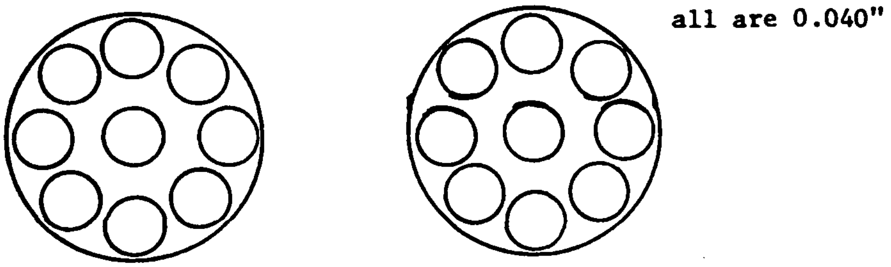
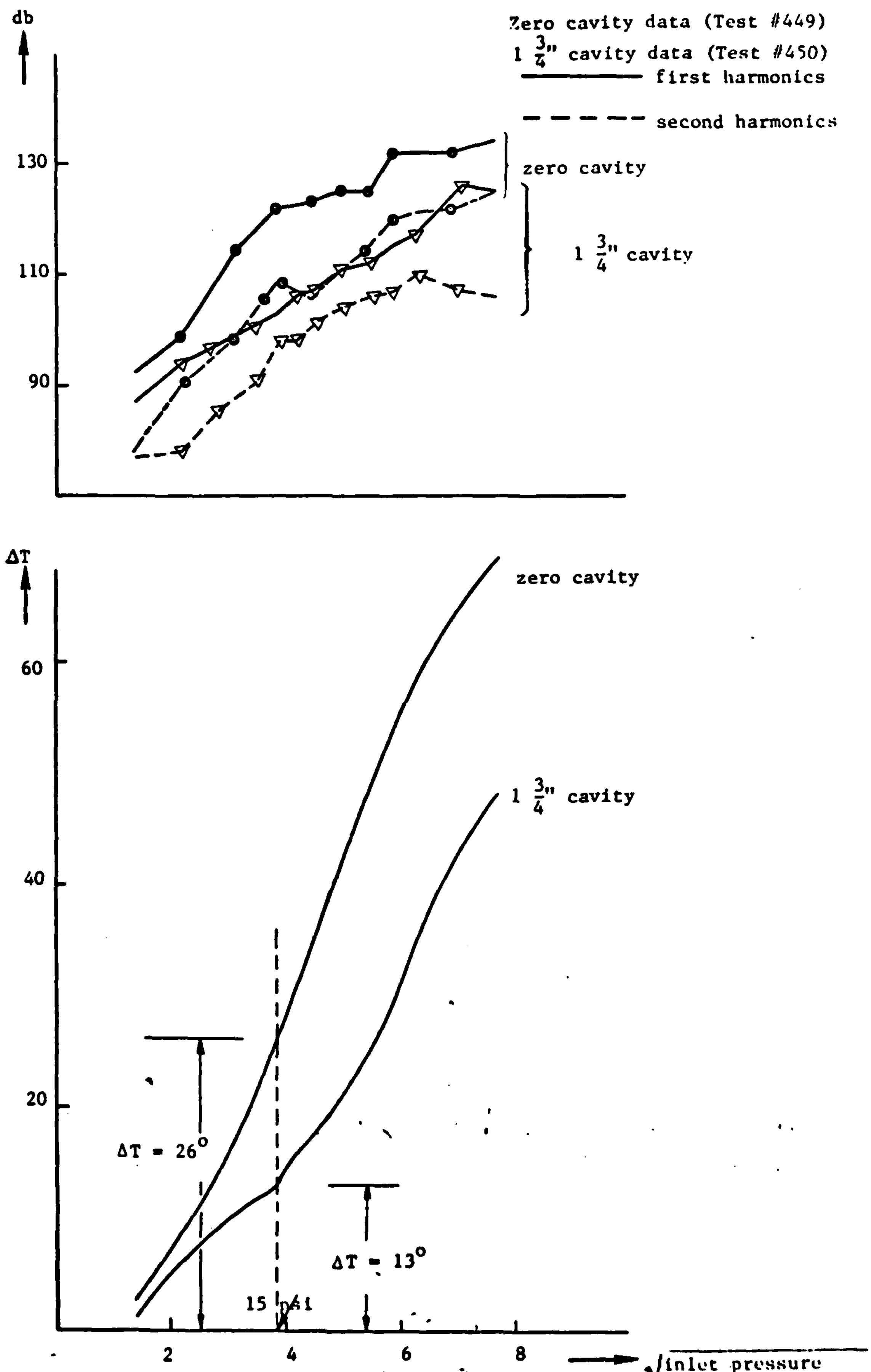


FIGURE 19

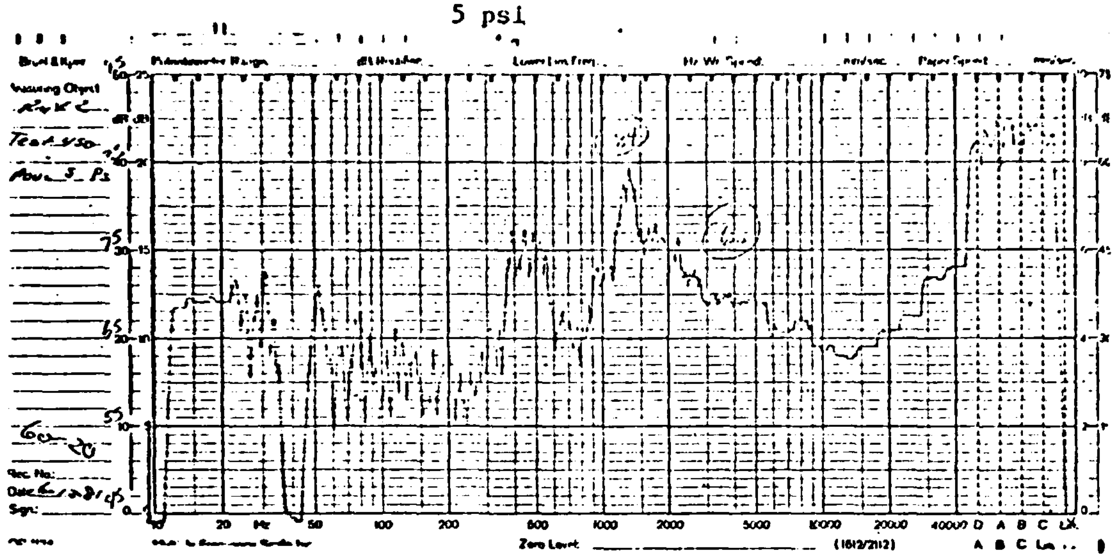


db
Zero cavity data (Test #449)
1 3/4" cavity data (Test #450)
first harmonics
second harmonics
130
110
90
zero cavity
1 3/4" cavity
ΔT
60
40
20
zero cavity
1 3/4" cavity
ΔT = 26°
ΔT = 13°
15 psi
2
4
6
8
√inlet pressure (psig)

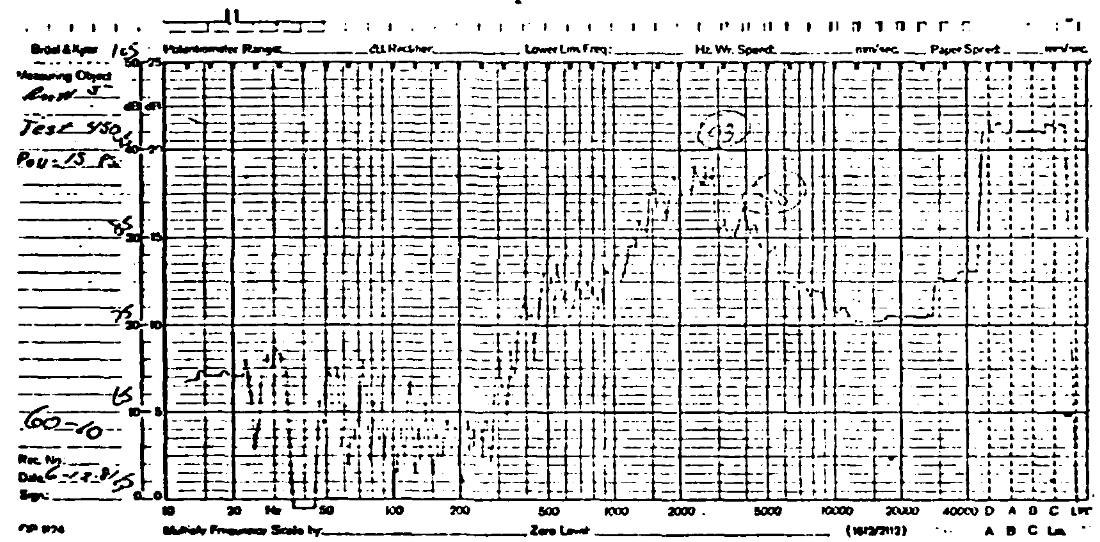
FIGURE 20

$1\frac{3}{4}$" Cavity (Test No. 450)

5 psi



15 psi



60 psi

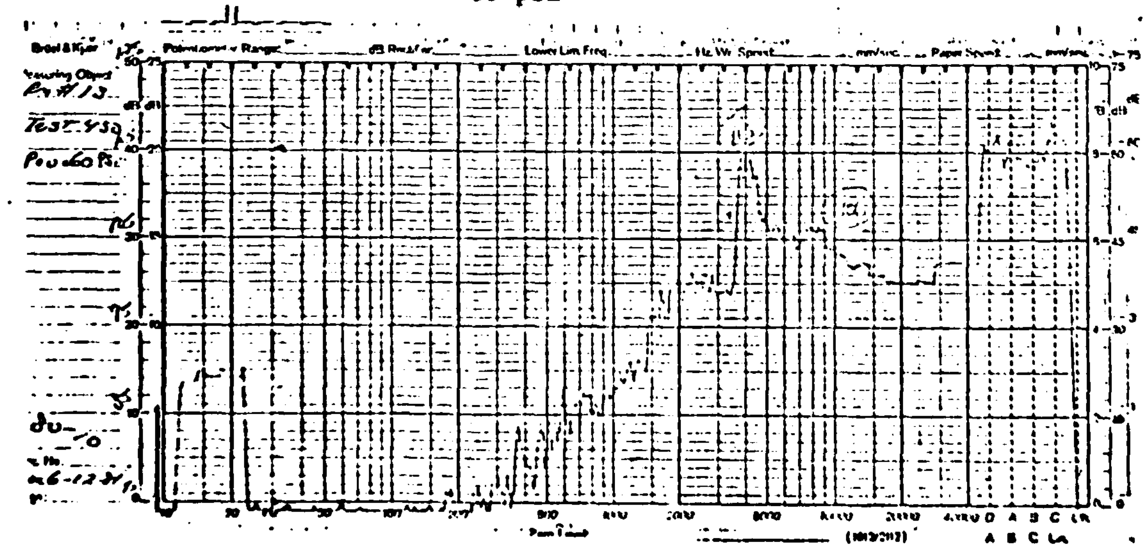


FIGURE 21

4. *Implication of the Present Program as Related to Aircraft Gas Turbines*

Once confirmed by further investigations to be carried out in Phase III, the applications of the program to the aircraft engine technology are:

(a) By explicit recognition of the dependence of vortex whistle upon the governing parameters as found in the present investigations, it is possible to avoid the structural failure of aircraft engines by detuning the natural frequency of various engine components away from the descrete frequency.

(b) By being cognizant of the acoustic characteristics of vortex whistle, one can conduct diagnosis of engine noise and identify the vortex whistle out of the other pure tone noise; this will aid in the effective noise suppression.

(c) The deformation of steady flow field induced by the vortex whistle implies that in the steady aerodynamic design of rotors/stators and in interpreting the steady data, due consideration may have to be given to this acoustic streaming effect.

(d) The positive exploitation of the vortex whistle and the induced temperature separation to enhance the turbine cooling may lead to the reduction of specific fuel consumption.

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- "Vortex Whistle - An Unsteady Phenomenon in Swirling Flow in Turbomachinery and its Implication" presented at joint NASA, AF/Navy Symposium on Aeroelasticity of Turbine Engines, NASA Lewis Research Center, Cleveland, OH, October 27 - 29, 1980.

- "Vortex Whistle" a second C. E. Danforth lecture on Airbreathing Propulsion, University of Cincinnati, November 17, 1980; also AiResearch Manufacturing Company, Pheonix, AZ, December 23, 1980; Detroit Diesel Allison, Indianapolis, Indiana, April 10, 1981.

- "Vortex Whistle: An Unsteady Phenomenon in Swirling Flow and its Effect Upon Steady Flow Field", by M. Kurosaka, AIAA Paper No. AIAA-81-0212, presented at AIAA 19th Aerospace Sciences Meeting, January 12 - 15, 1981, St. Louis, Missouri.

- "Acoustic Streaming Effect and Energy Separation in Swirling Flow" by M. Kurosaka (submitted for publication).

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This annual report covers the second phase of investigations into the unsteady swirling flows.

The overall objective of the entire program is to acquire fundamental understanding of a phenomenon characterized by violent fluctuations occuring in swirling flows in gas turbines; this flow instability, dubbed here as "Vortex Whistle", is known to be capable of causing severe fatigue failure in gas turbine components. Although the phenomena of 'Vortex Whistle' have never remained unrecognized, perhaps for the reason that they appeared in seemingly unrelated incidents under-

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various disguise, no comprehensive investigation appears to have been embarked upon. In addition, in spite of the fact that the vortex whistle is a pure tone noise and distinctly audible, its role as a source of aircraft engine noise has never been recognized. Furthermore, when the vortex whistle becomes intense, it induces a change in the steady flow field, the total temperature being spontaneously separated in the radial direction (the Ranque-Hilsch effect). Not only its implications to the study aero design of turbomachines are of obvious importance, but also this appears to offer an unmistakable clue to the puzzling Ranque-Hilsch effect.

In Phase I activity reported previously, the analytical framework of the phenomenon has been laid out; its unsteady characteristics were established and the induced radial deformation of steady flow field -- the total temperature separation -- has been explained.

In phase II reported in detail herein, the experiments were conducted for a swirling flow within the simple geometry of a single pipe and the results indeed verified the following key features of the analysis: (a) the presence of the vortex whistle whose frequency changes proportionately to the flow rate and the confirmation of it as the first tangential mode of a spinning wave, (b) the existence of the second harmonic with predicted characteristics, which support the expectation that the acoustic streaming is present and (c), by installing the acoustic suppressors and attenuating the amplitude of the vortex whistle at various frequencies, the amount of temperature separation in the radial direction is reduced; this substantiates the direct connection between the vortex whistle and the Ranque-Hilsch effect.